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SUMMARY OF THE NOAA/UTAH ATMOSPHERIC MODIFICATION PROGRAM: 1990-1996

September 1998

U.S. DEPARTMENT OF THE INTERIOR
Bureau of Reclamation
Technical Service Center
Water Resources Research Laboratory
River Systems and Meteorology Group

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13. ABSTRACT (Maximum 200 words) This final report summarizes physical investigations into the artificial nucleation ("seeding") of winter mountain clouds in central Utah during 1990-96. Program goals were to evaluate the effectiveness of the Utah operational cloud seeding program and to recommend improvements. Field programs employed a wide variety of instrumentation systems. Sophisticated numerical modeling was used in conjunction with the observational programs. Amounts and distributions of SLW (supercooled liquid water) cloud were investigated, as was transport and dispersion of ground-released seeding agents and tracer gases. Several experiments directly monitored ice crystals and snowfall rates resulting from either silver iodide (AgI) or liquid propane seeding. Results showed frequent SLW in excess of natural conversion to snowfall, suggesting significant seeding potential. The SLW was concentrated near the terrain where temperatures were relatively warm. When valley-released AgI was transported to cloud levels, resulting ice crystal formation was usually too limited for significant snowfall augmentation. However, marked enhancement of ice crystal concentrations and snowfall rates resulted from a number of high altitude releases of both AgI and liquid propane. Propane seeding was effective within even slightly supercooled cloud. Several recommendations were given for improving the operational seeding program's effectiveness.				
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**SUMMARY OF THE NOAA/UTAH
ATMOSPHERIC MODIFICATION
PROGRAM: 1990-1996**

by

Arlin B. Super

**River Systems and Meteorology Group
Water Resources Services
Technical Service Center
Denver, Colorado**

September 1998

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1. BACKGROUND AND INTRODUCTION

1.1 General Background

This is the Final Report by Reclamation (Bureau of Reclamation) for a multi-year project which investigated the effectiveness of an operational weather modification (cloud seeding) project in Utah. This applied research was done in cooperation with the NOAA (National Oceanic and Atmospheric Administration) AMP (Atmospheric Modification Program) and the Utah Division of Water Resources. While the Utah portion of the NOAA AMP (hereafter NOAA/Utah AMP) began several years earlier, the cooperative program discussed herein began late in 1989. At that time, Reclamation agreed to a Utah Division of Water Resources request that the author serve as the Principal Investigator for the NOAA/Utah AMP. The author continued in that capacity through 1996, at which time NOAA AMP funding was terminated by the U.S. Congress. Some additional analyses were performed after 1996 as reflected in this report.

The NOAA AMP program was conducted for several years in cooperation with the states of Arizona, Illinois, Nevada, North Dakota, Texas, and Utah as discussed by Golden (1995). The Navajo Nation joined the program in 1994. However, the late 1996 program termination effectively ended federally funded weather modification research in the United States for the time being. This is very unfortunate considering the potential importance of this emerging technology which may be able to provide significant rainfall and snowfall enhancement under favorable circumstances.

Operational (applied) weather modification (often called "cloud seeding") continues at many locations within the United States, especially in the western states and the Great Plains. Many other nations have been increasing their involvement in weather modification research as well as operations. The potential importance of rain and snow augmentation through properly applied cloud seeding is sufficient to stimulate progress in this complex field (Bulletin American Meteorological Society 1992). For example, the Seventh World Meteorological Organization International Scientific Conference on Weather Modification will be held in Thailand during February 1999 to discuss continuing progress.

It was agreed at the onset among the three cooperating agencies of the NOAA/Utah AMP that preference would be given to publication of results in the open refereed literature, such as the *Journal of Applied Meteorology* and *Journal of Weather Modification*, and in papers presented at scientific conferences. Production of large and detailed project reports, with their limited readership, was avoided by Reclamation scientists. Accordingly, this report consists of a program overview (sections 1-7) plus a compilation of summary information from the 29 journal articles and conference papers published in recent years under the sponsorship of the NOAA/Utah AMP. These publications resulted from research done by a number of groups involved in the program during this decade. In addition to Reclamation, those groups included the University of Nevada DRI (Desert Research Institute), the University of North Carolina at Asheville, the University of Utah, NCAR (National Center for Atmospheric Research) and NAWC (North American Weather Consultants). NAWC is the private company which has conducted the Utah operational cloud seeding program since 1974 (Griffith et al. 1997).

The NOAA ERL (Environmental Research Laboratories) also had a major role in this program. This agency provided an instrumented cloud physics and plume tracking aircraft for two major field programs, including pilots and technical personnel needed to support the sophisticated instrumentation systems. The NOAA/Utah AMP program was greatly enhanced by the NOAA ERL involvement.

1.2 Objectives and Research Reported

The research reported herein is based on the last several years of the NOAA/Utah AMP when field work was conducted on the Wasatch Plateau (hereafter Plateau) of central Utah, approximately between the towns of Fairview and Price. Earlier work was conducted on the Tushar Mountains of southern Utah. That work, which has its own body of publications (e.g., Huggins and Sassen 1990), is not discussed in this report. The single exception is the paper by Sassen and Zhao (1993), which is quite relevant to the Plateau findings and was published during the Plateau phase. A review of the earlier years of NOAA AMP work, with an extensive list of references, is given by Reinking (1992).

The NOAA/Utah AMP had two main objectives. First, the program was designed to *physically* evaluate the effectiveness of the Utah operational seeding program which has been partially funded by the State of Utah. Second, the program was to recommend to the Utah Division of Water Resources any changes which might improve future effectiveness of the operational seeding program. The operational program's goal was to increase the high mountain snowpack, which should lead to spring and summer streamflow augmentation (Super and McPartland 1993). Numerous findings and recommendations which could improve the operational program are to be found in the articles and papers summarized herein. Any decisions to implement such recommendations are the responsibility of the Utah Division of Water Resources and cooperating local water management agencies which jointly fund the operational program.

1.3 Problems with Statistical Evaluations

Three statistical evaluations of the operational program have been reported by Thompson and Griffith (1981), Griffith et al. (1991), and recently by Griffith et al. (1997). The reader is referred to these same articles for details of the operational program which used valley-based AgI generators, typically spaced on the order of 16 km apart (Griffith 1996). A small minority of all generators were sited in or near canyon mouths which could help transport and dispersion over mountainous terrain.

While all three of the statistical evaluations have suggested seasonal snowfall increases in the 10-20 percent range, one should be very cautious about accepting such indications. Griffith et al. (1997) correctly point out that their (statistical) techniques, "are not as rigorous or scientifically acceptable as is the randomization technique used in research." A sizeable body of literature exists which discusses the many difficulties of after-the-fact statistical analysis of operational seeding programs and why such attempts should be viewed with caution. Dennis (1980) and Gabriel (1981) discuss some of the problems that can result from improperly applied statistical approaches. Most of these arguments will not be repeated here. However, a major problem is the lack of any randomization with operational seeding programs, considered by many statisticians and meteorologists as essential for valid statistical testing. Target-control analysis of the type applied to Utah's operational seeding program must assume that precipitation relationships are stable over decades. This assumption presents a major difficulty (Dennis 1980). In the Utah analyses, these relationships are assumed stable over long distances, from central and southern Utah target gages well into Nevada and Arizona where control gages were selected. But it is well known that precipitation relationships can change over time and space for a variety of reasons ranging from large scale climatic changes (e.g., El Nino) to local changes in the environment of a precipitation gage (e.g., growth of vegetation affecting gage catch).

The three analyses cited above were done by the company hired to conduct the operational seeding. While it is common practice for cloud seeding operators to analyze their programs, statisticians have pointed out that this approach can lead to bias, favoring positive results. Dennis (1980) discusses a

number of ways of reducing bias in analysis of operational programs so that some useful information can be gleaned. For example, target and control gages should be selected and made known before a project starts.

Each of the three analyses cited above used a markedly different set of control gages and target gages. For example, two Arizona control gages were used in the 1981 analysis, none in the 1991 analysis and four totally different Arizona gages in the 1997 analysis. Some changes in gage selection may be necessary as gages are discontinued or relocated. However, such changes are unfortunate because consistent results from each analysis, based on the same target and control gages, would be more convincing.

Because of these and other problems with post-hoc statistical analysis of the Utah operational program, the Utah Division of Water Resources decided that physical evidence was needed to better evaluate the operational program. Accordingly, the NOAA/Utah AMP was heavily based on physical observations and reasoning, including sophisticated numerical modeling.

1.4 Selection of Wasatch Plateau Experimental Area

Soon after the author began to serve as Principal Investigator for the NOAA/Utah AMP, late in 1989, observational emphasis was shifted from the Tushar Mountains of southern Utah to the Wasatch Plateau of central Utah. This shift in the experimental area occurred because of several practical considerations, which significantly improved field observations. A limited winter field program was conducted during early 1990 on both the Wasatch Plateau of central Utah and the Wasatch Range just east of Salt Lake City (Super and Huggins 1992a, 1992b). Both are long north-south mountain barriers which should minimize transport of valley-released seeding material around them. However, the Plateau offered several advantages for field observational studies including less rugged terrain which permitted in-cloud aircraft sampling much closer to the barrier top, and all-weather roads across and along the Plateau, permitting widespread surface sampling by instrumented vehicles and access to fixed installations. The importance of low-level instrumented aircraft sampling and instrumented vehicle sampling along the Plateau's all weather highways, cannot be overemphasized. It has simply not been practical to obtain such observations for other mountain regions, with a few exceptions like the Grand Mesa of western Colorado (Super and Boe 1988). Aircraft sampling over the Plateau was conducted under special waivers from the Federal Aviation Administration. This procedure allowed flight to within 300 m of nearby *highest* terrain, while standard flight rules require 600 m minimum separation over mountainous terrain. Moreover, lowest sampling passes were made in a terrain-following mode, rather than flying at a constant altitude (Super 1995), which required exceptional piloting and navigation by the NOAA pilots. This practice and the special waivers resulted in lowest aircraft observations typically within 600 m of the Plateau top. In spite of the unusually low level sampling, the aircraft often could not descend into ground-released seeding plumes or significant SLW cloud because both were in shallow layers over the terrain.

The relative uniformity of the Plateau, with the broad Sanpete Valley to the west and parallel barrier farther westward (San Pitch Mountains), provided simplicities for airflow trajectories and numerical modeling efforts compared with more complex and rugged terrain. Nevertheless, the Plateau is believed to be reasonably typical of most of Utah's north-south oriented mountains targeted by the Utah operational seeding program.

1.5 Experimental Field Projects

During the years under discussion, three limited and two major field programs were held. The limited, early 1990 program was conducted on the Wasatch Range and Wasatch Plateau, as discussed by Super and Huggins (1992a, 1992b).

Major field programs were held for 2 month periods on the Plateau during early 1991 and early 1994 (both mid-January to mid-March). Major equipment used during these programs included:

- The NOAA Beechcraft King Air C-90 (N46RF) cloud physics and plume detection aircraft
- fixed and mobile microwave radiometers for monitoring vertically integrated liquid water and water vapor
- weather radar
- fixed and mobile ground-based detectors for AgI (silver iodide) and SF₆ (sulfur hexafluoride) tracer gas
- valley and high altitude AgI seeding generators and SF₆ release equipment
- recording precipitation gage networks
- local rawinsonde releases
- automated weather stations

More information on these programs is provided in several papers summarized herein (e.g., Super 1994, 1995).

Limited field programs took place on the Plateau during the 1994-95 and 1995-96 winters. These programs used a single, high altitude release site with AgI and SF₆ release capabilities and automated weather observations. A single target to detect the effects of seeding was operated on the west edge of the Plateau top, as discussed by Super and Holroyd (1997). The target station was equipped to observe AgI, SF₆, ice particle characteristics (by 2D-C laser probe), and supporting weather information.

1.6 Report Structure

The remainder of this report is made of 8 sections followed by references. The section titles are:

Section 2. Availability of Supercooled Liquid Water.

Section 3. Transport and Dispersion of Ground-Released Seeding Agents and Tracer Gas.

Section 4. Results of Physical Cloud Seeding Experiments.

Section 5. Numerical Modeling Results.

Section 6. Miscellaneous Associated Work.

Section 7. Summary and Recommendations.

Section 8. Selected Portions of the 29 Articles and Conference Papers.

Section 8 makes up the bulk of this report. It summarizes the 29 published articles and conference papers by several authors associated with the NOAA/Utah AMP. These articles and papers were published from 1992 to 1998. Most summaries consist of the abstracts or introductions, plus any summary, conclusions, and recommendations sections from each paper. These abbreviated versions of the original publications provide an overview of the considerable and wide-ranging research done during the Plateau program. References cited in the various publications are often not listed in this report's reference list, which contains only the 29 summarized papers and articles plus the additional references cited in sections 1-7. The reader is referred to the original publications for the substantial additional detail provided in them.

The original published form of the 29 articles and papers summarized herein would total hundreds of pages of text and figures, representing a significant body of work. In addition, numerous project reports and field program operations plans were produced during the NOAA/Utah AMP. This additional information is not discussed here.

2. AVAILABILITY OF SUPERCOOLED LIQUID WATER

2.1 Background Information

It is well known that a necessary (but not sufficient) condition for winter orographic cloud seeding to be effective is the availability of SLW (Supercooled Liquid Water) in excess of that naturally converted to snowfall. Successful seeding also requires transport and dispersion of seeding agents into the SLW clouds in sufficient concentrations to convert significant quantities of SLW to ice particles. Moreover, the conversion must take place where sufficient time and distance remain for the seeded particles to grow to snowflake sizes which settle to the mountain surface before sublimating in the lee subsidence zone. All of this must happen in an ever-changing and complex airflow and cloud environment. While it is sometimes convenient to consider winter orographic clouds as semi steady-state entities, they are actually changing rapidly on a wide range of spatial and temporal scales.

Many operational winter orographic cloud seeding programs and a number of experimental projects have *assumed* the presence of abundant SLW. However, few programs have made significant efforts to test this crucial assumption. The NOAA/Utah AMP put considerable effort into investigating spatial and temporal SLW distributions, using both observations and sophisticated numerical modeling. Indeed, documentation of SLW was the first major scientific objective of this program.

Several of the studies later summarized dealt with the important topic of SLW. These include Huggins (1992), Sassen and Zhao (1993), Super and Huggins (1993), Super (1994), Huggins (1995), Super (1995a), Huggins (1996), and Wetzel et al. (1996). Observations of SLW were made by tower-mounted icing rate meters, sensors carried by the NOAA instrumented aircraft, and by both fixed and mobile microwave radiometers. A mobile microwave radiometer was first deployed in the field during the NOAA/Utah AMP, as discussed by Huggins (1992, 1995) and Wetzel et al. (1996). It proved invaluable in mapping SLW distributions over the Plateau.

The general portrayal of SLW over the Plateau in the articles just noted is similar to findings from other mountainous regions, as reviewed by Super (1990). He noted that, "There is remarkable similarity among the research results from the various mountain ranges. In general, SLW is available during at least portions of many storms. It is usually concentrated in the lower layers, and especially in shallow clouds with warm tops. Average integrated amounts are normally limited implying low cloud liquid water contents, in agreement with aircraft observations."

The articles cited herein agree with the Super (1990) portrayal and expand upon it. Seasonally, a significant portion of the SLW flux is not converted to snowfall during passage over the Plateau. This finding suggests the availability of sufficient "raw material" for seeding to have a significant impact on snowfall, *provided* that seeding can convert a significant portion of the SLW flux to snowfall. The seasonal SLW flux is concentrated in a few large storms that are efficient snowfall producers during portions of their passages but inefficient during other phases. Super and Huggins (1993) considered the SLW flux across a number of mountain barriers. They concluded that seeding may be appropriate both when SLW is abundant and when it is limited. The relatively rare hours with large SLW amounts produce significant flux. But the numerous hours with small SLW amounts also produce significant flux over the course of an entire winter.

2.2 Field Observations of SLW

Huggins (1995) presented seasonal average portrayals of the cross-barrier SLW distribution over the Plateau. That work and other articles herein demonstrate the expected formation of SLW by forced orographic uplift over the west (windward) slope of the Plateau. Embedded convection, usually weak, enhances SLW production during some storm phases, and maximum SLW amounts are found above the windward slope. The gravity wave mechanism can also enhance SLW production as discussed in section 5. Snowfall often begins to reduce SLW amounts by the time cloudy air reaches the Plateau top's west edge, and the reduction continues as air flows eastward across the top (Huggins 1995). Both snowfall and subsiding airflow during passage across the Plateau lead to substantial SLW reduction. The SLW is largely depleted by the Plateau top's east (downwind) edge, approximately 10 km from the west edge.

Sassen and Zhao (1993) used lidar, microwave radiometer, and other observations to investigate SLW over the Tushar Mountains, about 175 km southwest of the Plateau experimental area. They demonstrated that SLW was usually found at barrier levels in the 0 to -10 °C range. Sassen and Zhao (1993) concluded that SLW cloud thickness was often only 500 to 800 m, with some SLW clouds nearly 1,000 m thick. That finding, along with layer temperature observations, led to their important conclusion that there was only a limited "window" for AgI seeding success. This "window" involved the upper portions of relatively warm SLW clouds with base temperatures warmer than -7 °C. Clouds with tops colder than -12 °C appeared to efficiently convert SLW to ice particles. Silver iodide is not effective for ice particle formation for temperatures warmer than -6 °C even when high AgI concentrations are present. With the limited in-cloud AgI concentrations resulting from operational seeding, there is often little opportunity for the seeding to be effective.

Super (1994) discussed the implications of almost continuous observations during the early 1991 two month field program. Measurements included SLW by microwave radiometer, gage precipitation, AgI by acoustical ice nucleus counter, and supporting observations. Super (1994) concluded that the SLW flux over the Plateau top's windward edge well exceeded the average snowfall over the Plateau top, suggesting that seeding might have the potential to convert some of the "excess" flux to additional snowfall. Moreover, many of the wetter hours had no detectable snowfall. These findings indicated significant seeding potential if a large fraction of the excess SLW flux could be converted to snowfall.

To put microwave radiometer vertically-integrated SLW amounts into perspective, Super (1994) compared them with observed hourly snow water equivalents. Accumulations for all 179 h with at least 0.01 inch observed by one or more of the three Plateau top gages provided the median hourly accumulation value of 0.015 inch. Half the total snowfall fell during the 83 percent of the precipitating hours with hourly accumulations of 0.05 inch or less. These data illustrate that mountain snowfall usually occurs at light rates over numerous hours as has been shown at a number of Rocky Mountain locations. Super (1994) calculated the equivalent snowfall rate if all SLW flux was converted to snowfall which fell uniformly across the 10 km wide Plateau top with a typical cross-barrier wind speed of 10 m s⁻¹. He showed that a vertically-integrated SLW amount in excess of 0.10 mm was needed to produce the median hourly snowfall accumulation of 0.015. Sixty-five percent of all hours with detectable SLW over the Plateau top's west edge were less than 0.10 mm. A significant portion of the SLW will be naturally converted to snow. Therefore, it follows that even when AgI seeding is successful, typical hourly accumulations would be limited. Moreover, hours with SLW amounts less than about 0.05 mm have very limited potential for snowfall production by seeding.

Super (1995a) presented the results from all six early 1991 experiments during which valley-released AgI was detected at lowest aircraft sampling levels over the Plateau. Observations of SLW were presented

from a Plateau top microwave radiometer and from aircraft sensors. Temperatures of SLW cloud reached by the AgI were usually only mildly supercooled, and estimated AgI ice nucleus concentrations were quite small. Aircraft measurements of ice particle concentrations and gage observations of snowfall indicated that any snowfall increases caused by seeding were at limited rates and occurred only when seeded clouds were colder than -9 °C at aircraft sampling altitudes.

2.3 Summary of SLW Findings

In summary, excess SLW often existed over the Plateau during at least portions of storm passages. During the early 1991 and early 1994 major field programs, SLW existed during post-frontal southwest flow and typically disappeared after frontal passage, as soon as Plateau top winds shifted to northwest. The SLW was confined to a shallow layer less than 1,000 m thick (often considerably less) above the Plateau where temperatures were typically mildly supercooled. Maximum SLW amounts were over the windward slope, in the orographic uplift zone, and amounts rapidly decreased during passage over the Plateau.

This general portrayal of SLW availability implies that effective seeding must create significant ice particle concentrations in the SLW cloud very soon after condensate is produced during transport of moist air up the Plateau's windward slope. Otherwise, growth times will be too limited for much snowfall production before the SLW is depleted. Accomplishment of ground-based seeding under these circumstances presents a significant challenge, especially with AgI, because the condensate is formed at only slightly supercooled temperatures. This challenge is not limited to the Plateau, as much of the Rocky Mountain region has similar shallow, slightly supercooled liquid water zones as reported by a number of authors.

3. TRANSPORT AND DISPERSION OF GROUND-RELEASED SEEDING AGENTS AND TRACER GAS

3.1 Background Information

Once the generalized distribution of SLW is known over a mountain barrier, it is of obvious interest to consider the transport and dispersion of seeding material to determine when, where, and in what concentrations the seeding material creates ice particles within the SLW cloud. Such transport and dispersion investigations were the second major research objective of the NOAA/Utah AMP.

The Utah operational seeding program has used AgI for many years, and that seeding material was given priority in the Plateau experiments. Liquid propane seeding, which can create ice crystals at higher temperatures than AgI, was also given significant attention, since it was found that much of the SLW was too warm for AgI to be effective. Sulfur hexafluoride tracer gas was often used to simulate seeding material transport and dispersion because it can be detected in small concentrations by fast-response instruments.

Unless otherwise stated, AgI in this report refers to the aerosol produced by burning AgI-NH₄I-acetone-water solutions in seeding generators. This solution has been used in the Utah operational seeding program, and it was used during the experiments discussed herein, including use of high altitude generators. This aerosol is known to operate by the contact nucleation mechanism, known to be a relatively slow process in typical orographic clouds that have limited cloud droplet concentrations.

3.2 Field Investigations of Transport and Dispersion

Super and Huggins (1992a, 1992b) considered the targeting of ground-released AgI during the field program of early 1990 from three different approaches. Silver-in-snow analysis was done with bulk snow samples from 10 sampling sites that should have been affected by the operational seeding program. There was little evidence that snow silver concentrations from seeded periods were greater than from nonseeded periods. These results were similar to earlier findings from the Tushar Mountains, but quite different from some projects in other states where seeding clearly increased snow silver concentrations by about an order of magnitude (e.g., Super and Heimbach 1983).

Real-time ice nucleus sampling was conducted well up Big Cottonwood Canyon while AgI releases were made with two generators in and above the canyon mouth. The AgI was routinely observed at the surface sampling location, which was about 500 m higher in elevation than the highest AgI generator. However, estimated AgI concentrations were small at prevailing SLW cloud temperatures.

The third approach reported by Super and Huggins (1992b) used aircraft sampling of ground-released AgI and SF₆ during near-storm prefrontal conditions. Sampling was during times when VFR (visual flight rules) flight operations were permissible, allowing sampling near the terrain. Four of the five aircraft missions of this type showed the AgI and tracer gas were confined to the lower atmosphere and were not transported over the Plateau. Plumes were found over the Plateau during part of the fifth mission, but estimated ice nucleus concentrations at prevailing cloud temperatures were quite limited.

Griffith et al. (1992) reported on IFR (instrument flight rules) aircraft sampling during the early 1991 program. Two case studies were selected for detailed discussion. Tracer gas released at the mouth of a

major canyon was found over the Plateau during the two aircraft missions at temperatures near -12 to -17 °C, respectively. Ice particle concentrations, calculated from SF_6 measurements, were sufficient for seeding to have been effective. However, it is suspected that natural cloud processes were quite efficient during the unusually cold cloud temperatures of one (March 6, 1991) of the two missions, as very little SLW existed above the Plateau top's west edge or at aircraft levels. Moreover, Super (1995a) reported that the maximum snowfall accumulation for the three Plateau top gages was only 0.01 inch during the entire 3 h experiment. Therefore, even if seeding increased the snowfall from this cold, weak storm, any enhancement was at the trace level.

The Plateau top snowfall during the second mission of March 2, 1991, was also quite limited, even though all eight valley AgI generators had been on for many hours, and AgI was abundant at relatively cold temperatures where SLW was plentiful. Super (1995a) reported only two of the three Plateau top gages detected snowfall during the experiment, and only at trace levels, in spite of a noticeable increase in the aircraft observed IPC (ice particle concentration) within the AgI plume(s). This finding is not encouraging for the valley seeding mode of operation. Even though the March 2 mission was flown under apparently nearly ideal conditions of seeding potential, and the valley-released AgI was transported to sufficiently cold SLW levels, any resulting snowfall was insignificant. It is speculated that AgI nucleation occurred too late for snowflake growth and fallout to occur on the Plateau.

Super (1994) examined SLW, snowfall, and AgI during 12 experimental days of the early 1991 season when valley seeding was being conducted. He concluded that the AgI concentrations measured *on top* the Plateau were insufficient for effective seeding unless the AgI reached SLW colder than about -12 °C. However, based on a later AgI generator calibration reported by DeMott et al. (1995), the estimated concentrations were too low as discussed by Super (1995a).

3.3 Analyses based on Recent Laboratory Studies

A subset of the early 1991 data reported by Super (1994) has been reexamined for this report using the latest calibration data for the NAWC AgI generator from DeMott et al. (1995). Values were used for "natural draft" conditions typical of light valley winds during seeding. An even 100 h from seven different relatively wet storm episodes met the criteria that the eight valley AgI generators had been on for at least 2 h to allow for transport time, microwave radiometer SLW equaled or exceeded 0.05 mm above the Plateau top's west edge, and the co-located NCAR acoustical ice nucleus counter operated properly with its cloud chamber temperature near -20 °C.

The NCAR counter mean INC (ice nucleus concentration) observations for the 100 h were multiplied by 3.0 to bring them in line with the CSU (Colorado State University) calibration of this device based on the isothermal cloud chamber results, also at -20 °C. A correction was applied to the cloud chamber values to compensate for dilution airflow (DeMott et al. 1995). For the uncorrected values usually provided by CSU generator calibrations, the two NCAR counters tested were found to indicate about two-thirds of the INC observed in the Isothermal Cloud Chamber, and there was excellent cross consistency between the two counters tested at CSU. A third NCAR counter, not tested at CSU, had been used during the Plateau experiments. Periodic side-by-side comparisons showed consistent results among all three units in the field.

An adjusted INC exceeding 10 L^{-1} at -20 °C can be considered clear evidence of AgI presence because the natural background observed during many hours without seeding was rarely that great, usually being in the 0 to 5 L^{-1} (adjusted) range. Ninety percent of the 100 sampled hours meeting the stated criteria showed evidence of AgI, with the adjusted INC exceeding 10 L^{-1} . Half the hours exceeded 500 L^{-1} , effective at

-20 °C, and 10 percent of the hours exceeded $2,000 \text{ L}^{-1}$. Therefore, the AgI was usually transported from the valley up to the canyon head, a vertical distance of over 900 m. This is remarkable when it is realized that valley-based inversions are common during winter storms. Most hours with SLW amounts of 0.05 mm or greater had weak embedded convection present, which likely assisted vertical AgI transport.

As discussed by Super (1994, section 8.3) these 100 sampled hours may be optimistic of typical hours with SLW present because of the frequency of embedded convection and associated large SLW amounts. Many other hours of observations were made that have not been reported when very large AgI concentrations were confined to a shallow layer over the Sanpete Valley. A large fraction of these hours also had SLW present above the Plateau, although average amounts were more limited than the 100 h sample just discussed. During a number of experimental periods, the only AgI that could be found with an instrumented vehicle carrying an NCAR counter were within about 100 m elevation of the valley floor. During a number of experiments when only background INC were found along the Plateau top, the vehicle was driven down a major canyon toward the town of Fairview in the valley. The INC effective at -20 °C would abruptly shift from background levels of $1\text{--}3 \text{ L}^{-1}$ within the canyon to many thousands per liter as the vehicle passed below the canyon mouth just above Fairview. The NCAR counter would become saturated with ice crystals so absolute INC cannot be quantified beyond stating that they were at least thousands per liter. Clearly, as the eight valley generators were operated hour after hour, they produced vast quantities of AgI aerosol, trapped in a shallow layer above their valley elevations. Valley winds during these events were no more than a light northward drift.

In spite of observations of trapped AgI during a number of experiments, it appears that the valley-released AgI was often transported to Plateau top altitudes when SLW was reasonably abundant as represented by the 100 h data set discussed above. However, it is necessary to consider the adjusted NCAR counter INC values in the context of typical Plateau top temperatures which are much warmer than the -20 °C cloud chamber operating temperature. For example, the median temperature during all 100 h was a mild -2.6 °C, while the median for the 50 wettest hours, with SLW exceeding 0.16 mm, was an even warmer -1.5 °C. The latest calibration of the NAWC generator shows that the effective INC at -6 °C, the warmest temperature sampled in the CSU Isothermal Cloud Chamber, is only 1/4 of 1 percent of that at -20 °C. Hence, even an adjusted NCAR counter INC of $2,000 \text{ L}^{-1}$ yields an estimated effective INC of 5 L^{-1} , considered too low for significant snowfall production (Super 1994, section 8.2). Furthermore, only 9 of the 100 h was colder than -6 °C at the Plateau top altitude of 2700 m.

A more recent data set by Holroyd and Super (1998) showed that the Plateau top temperature was colder than -7 °C during only 20 percent of AgI seeding experiments conducted during the 1994-95 and 1995-96 winters. Temperatures were even warmer during many other experiments when liquid propane seeding was attempted. These large data sets leave no doubt that temperatures near the Plateau top are typically only mildly supercooled during storm episodes.

The CSU generator calibration showed that at -8 °C the effective INC was 8 percent of that at -20 °C, while the effective INC increased to 33 percent at -10 °C. If the AgI concentrations measured on the Plateau existed at higher altitudes corresponding to these temperatures, the median effective INC would be 40 and 165 L^{-1} , respectively. Such concentrations would be considered sufficient for effective seeding. However, for typical in-cloud lapse rates, the stated temperatures would be about 800 and 1,100 m above the Plateau for the median Plateau top temperature of -2.6 °C.

Aircraft observations were made during six experimental days when valley-released AgI was transported to the lowest permissible aircraft sampling altitude, about 600 m about the average Plateau top terrain as reported by Super (1995a). Four of these experiments were conducted on some of the same days which provided the 100 h Plateau top data set just discussed. The aircraft missions showed that AgI

concentrations 600 m above the Plateau were typically more than an order of magnitude less than those measured on top of the Plateau, both at the fixed canyon head site and by an instrumented vehicle driven along the Plateau top's west edge. Some of the lowest aircraft passes failed to detect any AgI during these experiments. On some other experimental days the aircraft failed to detect any AgI even though many passes were made while abundant AgI concentrations (at -20 °C) were being monitored on the Plateau. The considerable body of aircraft observations from many experimental days has shown that AgI is rarely transported as high as 1,000 m above the Plateau, and then only in weak concentrations.

Another important factor to be considered is the rate at which AgI activates ice particles. The discussion above presents the most optimistic case in which calculations of effective AgI concentrations assume total nucleation by the aerosol. However, CSU Isothermal Cloud Chamber AgI generator calibrations are done over extended periods, often tens of minutes, to allow aerosol the time necessary to nucleate. NCAR counters are operated at very high cloud droplet concentrations to enhance nucleation during their limited cloud chamber residence time. But orographic clouds have limited droplet concentrations.

DeMott et al. (1995) show that the AgI aerosol produced by the NAWC generator and the AgI-H₂O-acetone-water solution operates by contact nucleation, a slow process. They calculated that, for a constant temperature, only about 7 percent of the potential yield would be realized during a 20 minute transit of this AgI aerosol through a natural cloud of 100 droplets cm⁻³. Simple calculations of transport times within SLW cloud over the Plateau show that AgI will be exposed to liquid cloud on the order of 20 minutes. Therefore, prior calculations of INC effectiveness, based on NCAR counter measurements and the CSU generator calibration, are probably overestimated by more than an order of magnitude. The sooner ice particles are formed within SLW cloud, the greater their probability of growing to snowflake sizes and settling to the surface before being transported beyond the mountain barrier.

These INC observations indicate a limited "window of opportunity" for effective AgI seeding since measurements have shown little evidence of significant ice particle enhancement in cloud warmer than -9 °C. This finding is in agreement with the Tushar Mountains observations presented by Sassen and Zhao (1993). Both data sets demonstrate the difficulty of effective ground-based AgI seeding with mildly supercooled orographic clouds typical of Utah's mountains. Seedable opportunities are limited to the colder "tail" of the distribution of SLW temperatures.

Further evidence on this point is provided by the Bridger Range Experiment conducted in the colder climate of southwestern Montana. Statistical analysis of that experiment by Super and Heimbach (1983), later supported by aircraft microphysical observations (Super and Heimbach 1988), strongly suggested that AgI seeding from high altitude sites was effective only when ridge top (equivalent to Plateau top) temperatures were colder than -9 °C. About half the Bridger Range periods were that cold. But if one assumes similar vertical transport of AgI over the Bridger Range and the Plateau, as aircraft observations have indicated, a much smaller fraction of Utah storm periods would be seedable with AgI. This comparison further indicates that effective ground-based AgI seeding in Utah is limited to a fraction of the time that SLW is available. Moreover, at least a portion of the apparent success of the Bridger Range seeding may have been due to the frequent in-cloud operation of the AgI generators, with instantaneous ice particle production caused by the supersaturated conditions very near the generators (Finnigan and Pittner 1988). It is known the AgI generators produce abundant quantities of water while consuming propane fuel and the acetone in which the AgI is mixed. This can lead to local condensation-freezing as soon as the AgI aerosol is exposed to the supersaturated but supercooled cloud. This rapid ice nucleation mechanism will not occur with valley-released AgI.

3.4 Seeding-Caused Snowfall Calculations

Laboratory observations have indicated that the NCAR counters used in the Plateau studies were in reasonable agreement with CSU Isothermal Cloud Chamber results. Plateau-top and aircraft observations of ice particle concentrations have been shown to be in reasonable agreement with NCAR counter estimates of effective ice nucleus concentrations using CSU generator calibrations to extrapolate to temperatures warmer than the -20 °C used by the NCAR counter. Therefore, it is reasonable to use CSU generator calibration data to calculate upper limit snowfall increases possible with the Utah operational seeding.

It will be assumed in the calculations to follow that seeding-caused ice crystals do not participate in any secondary ice "multiplication" process. That is, any single AgI aerosol particle will have the potential to produce only one ice crystal. There is ample justification for this assumption. The conditions necessary for significant ice particle multiplication to occur are reasonably well understood (Mossop 1985). Such conditions are not characteristic of Rocky Mountain orographic clouds, especially at the colder temperatures where AgI can be effective.

The latest CSU calibration of the NAWC generator, for the AgI solution used in Utah's operational seeding, can be used to show that it is highly unlikely that the operational seeding produced the snowfall increases suggested by NAWC's published statistical analyses. The normal April 1st snow water equivalent found at snow courses in or near the Plateau's experimental area is about 50 cm. The most recent statistical analysis by the seeding operator (Griffith et al. 1997) suggests that about a 15 percent seasonal increase was achieved, equivalent to 7.5 cm for a normal winter. Using the typical AgI generator spacing of 16 km (Griffith 1996) and approximate Plateau top width of 10 km provides an estimated area per generator of 1.6×10^{12} cm². The water volume provided by a 7.5 cm increase would be 1.2×10^{13} cm³, equivalent to 1.2×10^{13} g of water mass.

We will make the highly optimistic assumption that *all* the AgI aerosol reached SLW cloud at a relatively cold temperature of -8 °C. This is contrary to the large NOAA/Utah AMP data set which indicates that only limited AgI reaches cloud temperatures that cold. The CSU calibration indicates the generator output at -8 °C is 1.4×10^{14} crystals g⁻¹ for natural draft conditions. We will make the additional highly optimistic assumption that *all* the available aerosol nucleated ice crystals at that temperature. Then the resulting seasonal output of ice crystals can be calculated as 2.8×10^{17} , since generator output is 8 g h⁻¹ (Griffith et al. 1992), and the generators are operated for about 250 h per 5 month winter (Super and Huggins 1992a, table 2). These crude but conservative calculations yield an average mass per ice crystal of 0.04 mg per crystal. But as discussed by Super and Huggins (1992a) and Super (1994), observations from a number of locations show that the mass of a "typical" natural ice crystal is less than half that value. Furthermore, seeded ice crystals are likely to be smaller because of less in-cloud residence time.

These calculated results would require that *all* AgI reached a significantly colder temperature than supported by the multitude of field observations. In reality, AgI was sometimes trapped in the upwind valley and did not reach SLW cloud. When it was transported over the Plateau, the bulk of the AgI was typically in a thin layer where temperatures were too warm for significant ice crystal formation. Often, this layer contained negligible SLW because it was consumed by natural snowfall processes. In-cloud residence times provided a further limitation to AgI nucleation ability. Finally, natural snowfall could be expected to sweep out some AgI aerosol. For all these reasons, the above calculations of the typical ice crystal mass which AgI would need to produce to achieve a 15 percent seasonal snowpack increase are absurdly low. During the fraction of the time when storm conditions made it possible for seeding to create ice crystals, they would have to grow to unrealistically huge sizes (masses) to produce the claimed

15 percent increase. Therefore, those supposed increases could not be the result of the Utah operational seeding program according to current physical understanding.

Additional information on transport and dispersion is provided in the following two sections. It will be shown that release from high altitude locations, well up the windward slopes of the barrier, results in much more consistent transport over the Plateau. However, plume widths may be reduced as compared to valley releases. The vertical dispersion of the high altitude releases is not believed to be markedly different from valley releases. Both plume types were often found at, and limited to, the lowest aircraft sampling levels and below. Both plume types were sometimes too shallow for detection at even the lowest permissible aircraft sampling altitudes.

4. RESULTS OF PHYSICAL CLOUD SEEDING EXPERIMENTS

4.1 Background Information

There is no doubt that AgI released into sufficiently cold SLW cloud will produce multitudes of embryonic ice particles. The same result is achieved when liquid propane is expanded into even slightly supercooled liquid cloud. The challenge is to create the seeded ice particles at such locations that their subsequent trajectories will be within SLW cloud for a sufficient time (distance) to permit growth to precipitation sizes such that the particles will fall to the mountain surface before sublimating in the lee subsidence zone. Ideally, the tiny seeded crystals should be formed very soon after SLW condensate is produced as air is forced up a mountain barrier, is carried upward by embedded convection, is transported upward by gravity waves, or ascends by some combination thereof. Releasing AgI even at cloud base will not result in immediate nucleation unless the temperature is colder than -6°C .

Numerous attempts were made to document the effectiveness of AgI and propane seeding in creating ice particles and snowfall during the Plateau experiments. Most emphasis was placed on such documentation during the limited programs of the 1994-95 and 1995-96 winters, as summarized by Super and Holroyd (1997) and Holroyd and Super (1998).

With two exceptions previously noted (March 2 and March 6, 1991) and discussed by Super (1995a), all AgI and propane seeding experiments which demonstrated IPC enhancements used high altitude release sites well up the windward slope of the Plateau. Unless specifically mentioned otherwise, it can be assumed that high altitude seeding sites were used in the cases to be discussed.

4.2 Case Study Analyses

The first article in this series to document seeding-caused ice particles was by Super and Holroyd (1994). A several-fold enhancement in IPC was shown at aircraft levels for the February 17, 1991, experiment. The co-located AgI and SF_6 were both detected with aircraft instruments. Measurement of SF_6 with a fast-response detector allowed for precise delineation of the seeded zones. Seeding-caused IPC was near 70 L^{-1} at cloud temperatures of -13.0 to -15.5°C over the Plateau top's west edge.

Holroyd et al. (1995) presented a detailed analysis, with numerical modeling support, of the February 21, 1994, experiment. It was shown that high concentrations of ice particles were associated with measured and predicted plume locations sampled on the Plateau top with a 4-wheel drive vehicle, and above the Plateau with the NOAA aircraft. Ice particle concentrations and precipitation rates were enhanced by a factor of about 10 along the Plateau top's west edge highway, and by about a factor of 40 according to aircraft sampling above the west edge. Most growth was upwind of these sampling tracks, above the windward slope where SLW was concentrated. Aggregation of high concentrations of ice particles appeared to be the primary snowfall mechanism. Plateau top observations suggested that only limited precipitation reached the surface, perhaps 0.5 mm accumulation over a few hours at some gages. But no gages were available near the windward edge where most seeded snow likely fell.

Super (1995b) presented detailed analyses that demonstrated an obvious increase in IPC and snowfall associated with the propane seeding experiment of March 5, 1995. Less obvious but still fairly convincing evidence of IPC and snowfall enhancement was presented from an experiment on March 11, 1995. Light natural snowfall "contaminated" the impacts of propane seeding during the latter experiment.

Super (1996) showed another obvious case of IPC and snowfall enhancement caused by AgI seeding during relatively cold Plateau top temperatures (-10.7°C). This seeding, on December 15, 1994, produced about 1 mm additional snowfall on the Plateau top's west edge during the hour of seeding. The successful March 5, 1995, propane experiment at a Plateau top temperature of -4.5°C was again reviewed, and it was shown that AgI seeding soon after the propane seeding was ineffective under similar conditions.

Significant documentation of seeding-caused IPC and snowfall resulted from the 1994-95 and 1995-96 winter field programs. This could be expected since these limited, economical experiments were designed for that purpose. Moreover, it was practical to conduct many such experiments with only limited ground equipment and two to three field technicians. The basic design was to release seeding material, AgI or propane, in a brief "pulse" of one-half hour or one hour duration. The release point was on a high, exposed ridge only 4.2 km horizontal distance and 315 m below the instrumented "target" site located at the head of a major canyon. Prevailing southwest winds funneled the seeded cloud up the canyon and past the target. Ice particle characteristics and snowfall rates could be examined before, during, and after "plume" passage by the target.

Some experiments provided obvious IPC enhancement, and sometimes snowfall augmentation, when examined on a case study basis. However, seeding effects were not obvious in most of the experiments. Some of the failures to clearly demonstrate IPC increases were caused by cloud temperatures too warm for seeding agent effectiveness, especially when AgI was used. Other failures were due to short-term natural variability in snowfall rates which often masked the seeding-caused ice particles. It is likely that many of the seeding experiments created tiny crystals which were swept out by larger natural snowflakes and, therefore, were undetectable by the experimental design. Furthermore, abundant natural snow may have consumed all available SLW, thereby starving the embryonic seeded crystals. This series of experiments showed the difficulties of clearly demonstrating ice particle and snowfall production in the presence of even light natural snow. Orographic clouds are anything but steady-state, and natural snowfall rates often vary considerably over a few tens of minutes or less.

4.3 Statistical Analysis of Pulsed Seeding Experiments

When natural snowfall was nil to very light and seeding potential existed, obvious effects of seeding could be demonstrated (Super and Holroyd 1997). But such conditions occur during a minority of the time that orographic cloud is present. However, statistical analysis provided an overview of all similar experiments conducted during the 1994-95 and 1995-96 winters (Holroyd and Super 1998). There were indications of AgI effectiveness in creating small ice particles for target (Plateau top) temperatures colder than about -6°C . However, the number of such cases was limited because less than 20 percent of all seeding experiments had target temperatures colder than -7°C . Stronger evidence existed of propane-caused small ice particles, and even the difference between using one propane nozzle (1994-95 winter) and two (1995-96 winter) was evident. Snowfall increases caused by the seeded crystals were limited, as might be expected from the limited distance (4.2 km) and travel time (median 17 min) between seeding release and the target. This distance was purposely limited to maximize successful targeting as the seeded cloud was funneled up a major canyon.

Perhaps the most important finding of these "pulse seeding" experiments was that propane seeding was effective in producing ice particles even with slightly supercooled cloud at the dispenser site (-0.4 to -3.4°C). About 10 ice particles L^{-1} was typical at the target with one propane nozzle releasing about 3 gal h^{-1} , and 20 L^{-1} with two nozzles releasing twice that rate. As argued by Super (1994), a seeded IPC over a target in excess of 10 L^{-1} has the potential to produce meaningful snowfall. Holroyd and Super

(1998) confirm that view as their figure 3 shows only a small fraction of the many hours with significant natural snowfall at the target had IPC less than 10 L^{-1} . The target IPC during natural snowfall was usually between 20 to 200 L^{-1} . Some operational programs have attempted to enhance snowfall with estimated IPC near 1 L^{-1} . Such an approach would have a negligible chance of success in Utah and probably elsewhere.

Cases with target temperatures colder than -4°C were usually seeded with AgI, but no evidence of AgI ice particle production was evident with target temperatures warmer than about -6°C . As noted, periods with SLW cloud infrequently have Plateau top temperatures colder than -6°C , which seriously limits the "window of opportunity" for ground-based AgI seeding unless significant vertical dispersion occurs. These experiments did not sample above the target (Plateau top) elevation, but earlier work demonstrated vertical dispersion of AgI was limited.

5. NUMERICAL MODELING RESULTS

5.1 Background Information

Numerical modeling provided significant insight into the physical processes involved during winter orographic storms over the Plateau. The model used in these investigations was the sophisticated, three-dimensional, time dependent numerical model developed by T. Clark and associates at the National Center for Atmospheric Research.

Modeling results should be treated with caution until it is demonstrated that they are in reasonable agreement with observations. However, observations are limited in time and space and are impractical to make in some very important locations. Therefore, model results can "fill in" where observations do not exist, provided model results and observations are in good agreement where both exist.

The Clark model was applied to the Mogollon Rim of Arizona, as discussed by Bruintjes et al. (1995). They showed the model was quite successful in reproducing observed plume dispersion. The importance of gravity wave dynamics in the transport and dispersion of seeding material was demonstrated by their work.

5.2 Model Applications to the Wasatch Plateau

Heimbach and Hall (1994) discuss the Clark model and its application to the Plateau. They compared model results with a well-observed case from the early 1991 field season which involved seeding with valley AgI generators. Reasonable agreement was found with AgI plume positioning. Considerable pooling of AgI occurred within the valley, but a shallow layer was eventually transported over the Plateau. The importance of gravity waves for the vertical transport of seeding agent was demonstrated in agreement with the results of Bruintjes et al. (1995). Gravity waves were also found to be influential in the production of liquid water and its subsequent downwind depletion in zones of subsidence. The horizontal and vertical position of the seeding release point was critical in determining whether the model-simulated seeding agent was transported over the Plateau for particular conditions.

Modeling results also suggested that seeding from the San Pitch Mountains, the next barrier west (upwind) of the Plateau, might provide broader plumes, earlier nucleation, and opportunity for greater vertical transport. These factors might increase seeding effectiveness if embryonic seeded crystals that formed over the San Pitch Mountains were transported into the SLW condensate zone over the Plateau's west slope, where further growth and fallout could occur. A similar approach was apparently successful during the Bridger Range Experiment (Super and Heimbach 1983), although the valley between the barriers was narrower. The approach of seeding on the windward slopes of one barrier to affect another farther downwind should receive further consideration in view of limited growth times found over the Plateau (e.g., Huggins 1995).

Reasonable model agreement was found in the case of a high altitude ground release of AgI from the early 1991 field season reported by Holroyd et al. (1995). This experiment produced marked IPC enhancement on and above the Plateau top and apparently limited accumulations of snowfall. The heights to which model-simulated AgI plumes reached were in good agreement with aircraft measurements. The model's smoothed terrain failed to simulate some of the small-scale but important effects of major canyons which funnel the airflow. The model produced weak and shallow clouds which were driven orographically with

little buoyant contribution. Gravity waves were shown to be important for transport over the Plateau and produced a secondary maximum of tracer over the eastern portions of the Plateau.

Heimbach and Hall (1996) and Heimbach et al. (1997) modeled a well-observed case study during which AgI was released from three valley generators and tracer gas was released in a major canyon mouth. In spite of a surface inversion, the AgI was transported up and over the Plateau in a shallow layer, below minimum aircraft sampling levels. The model results suggest the initial vertical impetus for vertical transport was by the gravity wave mechanism. This was followed by orographic forcing in a more organized westerly flow. The observed confinement of the AgI to a shallow layer was predicted by the model simulation.

5.3 Modeling of Generalized Weather Classes

Valley AgI seeding was modeled for five generalized weather classes by Heimbach et al. (1998). A total of 46 rawinsonde observations from the early 1991 and early 1994 field programs were grouped into five classes according to temperature profiles. (Nineteen additional soundings did not fit within the five class criteria.) In general, the modeled results were in agreement with well observed case studies selected to represent each sounding. Some of the important results from the modeling include:

- a. A frequent tendency existed for a low-level northward drift of the valley-released AgI, parallel to rather than over the Plateau.
- b. Poor targeting resulted from valley releases during the two most stable classes. Thirty-seven percent of the classified soundings were in these two classes.
- c. The best targeting was with the most unstable class, which also had the coldest temperatures, thereby resulting in greater AgI effectiveness in ice particle production. Twenty-six percent of the classified soundings were in this class.
- d. Frequent negligible AgI effectiveness resulted even when AgI was transported over the Plateau because of warm prevailing temperatures.
- e. Strong upward motion existed over the valley under some stability and wind conditions because of gravity wave transport. This mechanism can significantly aid the transport of valley-released AgI, but its presence, magnitude, and location vary markedly with time.
- f. Mechanical forcing is important for AgI transport over the Plateau.
- g. In some conditions, there can be a westward and north westward drift of valley-released tracer in spite of organized westerly flow aloft.

5.4 Summary of Model Results

In summary, the Clark model results were in good agreement with field observations. Valley-released AgI was often trapped by surface-based inversions and usually drifted northward, parallel to the Plateau, rather than over it. Sometimes the drift was westward or north westward, contrary to flow aloft. Very large AgI concentrations were modeled (and observed) along the valley floor on several occasions after generators had been operated for several hours.

A gravity wave mechanism sometimes aided the vertical AgI transport even in the presence of inversions. The positioning of the gravity waves relative to the terrain and AgI generator locations was critical in determining whether vertical AgI transport occurred. Since gravity wave positioning varies with time, and AgI generators are at fixed locations, it can be argued that generators should be located at various distances west of the Plateau across the broad upwind valley. This latter approach was modeled by Heimbach and Hall (1994).

During more unstable conditions, the valley-released AgI was consistently transported over the Plateau. The AgI plumes were consistently shallow over the Plateau top, often below lowest aircraft sampling levels just 600 m above average Plateau top elevations. Prevailing cloud temperatures within the shallow plumes were frequently too warm for effective ice nucleation by the AgI.

It has been demonstrated by model-simulations and observations that valley-released AgI is transported over the Plateau during only a minority of hours with storm conditions. When transport does occur, the AgI plumes are often too warm for much ice nucleation. These two factors are in agreement with previous documentation from the Tushar Mountains of southern Utah (e.g., Sassen and Zhao 1993). These findings suggest that valley AgI releases should be augmented or replaced with other treatment technologies (e.g., high-altitude AgI releases and propane seeding) in order to increase the efficiency of the Utah operational cloud seeding program.

6. MISCELLANEOUS ASSOCIATED WORK

A number of topics were explored during the Plateau program that do not fit under the above section headings. Consequently, these are included here.

6.1 Effect of Type II Statistical Errors on Experimental Duration

Heimbach and Super (1992, 1996) explored the important problem of encountering type II statistical errors in past randomized weather modification experiments. A type II error occurs when an experiment fails to detect an actual response to seeding, usually because the experimental unit population is too limited. Many experiments did not estimate the duration (population size) needed to achieve an acceptably low probability of encountering a type II error, say 10 percent. If an experiment failed to indicate a seeding effect upon completion (usually determined by the sponsor's patience and available resources), the "failure" may have been caused by a type II error. The only valid conclusion from such an experiment is that it failed to demonstrate anything about seeding effectiveness. Unfortunately, the incorrect interpretation is often given; that is, that the seeding approach did not produce the desired effect.

When attempts were made to estimate the experimental duration needed to demonstrate real seeding effects, it was usually assumed that each treated unit would respond in the same manner. But a considerable body of physical evidence shows this assumption to be improbable. The effectiveness of seeding can be expected to vary widely depending upon cloud and airflow conditions. Heimbach and Super (1992, 1996) investigated the more likely possibility that different experimental units (storms or days) have different responses to treatment. They demonstrated that this more realistic response leads to much longer experimental durations than if every treated unit responded uniformly. This important finding raises the question of whether many of the past seeding experiments that were interpreted as failures were simply too brief to demonstrate real seeding responses. Of course, if their physical design was flawed, they should have failed whatever their duration. But the point is that little can be gleaned about the seeding effectiveness of many past statistical experiments because of the uncertainty of whether they had type II errors. While Heimbach and Super (1996) made recommendations for possible improvements in future statistical experiments, their main recommendation was that such experiments be postponed until a much improved physical understanding emerges. An improved physical understanding was the main goal of the Plateau work.

6.2 Runoff Increases Associated with Snowfall Enhancement

Super and McPartland (1993) reported on an investigation of likely runoff increases from an assumed seasonal snowpack increase of 10 percent. Cloud seeding programs are usually evaluated in term of seasonal percentage increases of snow water equivalent, but water users are interested in streamflow enhancement. Historical snow water equivalent and streamflow measurements were used from high elevation watersheds in the Upper Colorado River Basin. Drainages were selected for which streamflow measurements were not significantly affected by upstream diversions and were not regulated by upstream reservoirs. A simple linear regression analysis predicted seasonal streamflow increases between 6 and 21 percent. Ten percent or more additional runoff was estimated for most drainages for the assumed 10 percent snow water equivalent increase, an encouraging result. Reasons for differing responses were discussed which included variations in geology, vegetation, drainage slope, and aspect.

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6.3 New Instruments and Observational Approaches

A number of new instruments and observational approaches were developed and deployed during the NOAA/Utah AMP. For example, the mobile microwave radiometer (Huggins 1992, 1995, 1996; Wetzel et al. 1996) provided a useful new way to map SLW over a mountain barrier. This approach is particularly important when it is recognized that safety concerns often prevent instrumented aircraft from flying low enough to monitor the orographic cloud SLW field in the region where most snow particles grow.

Truck-mounted NCAR counters and SF₆ detectors were used in tracking plumes up and over the Plateau. One truck carrying plume detection equipment also had a vane-mounted 2D-C laser probe on a mast above it. The vane kept the probe pointed into the resultant wind as the truck was driven along the Plateau top, while the 2D-C strobe rate was controlled by an anemometer. Tower-mounted 2D-C probes, also pointed into the wind by vanes, provided similar ice particle observations at fixed locations (Super and Holroyd 1997). Use of vane-mounted 2D-C probes provided a new and more accurate means of observing ice crystals caused by seeding. As it became available, GPS (Global Positioning System) equipment was used to record truck and aircraft positions.

Super (1993) reported on testing of an automated, self-antifreeze-recharging, recording precipitation gage in a winter mountain environment. The gage was shown to be as accurate as the conventional Belfort Universal gage which requires manual service and chart reduction.

Two methods of estimating AgI ice nuclei concentrations effective at cloud temperatures sampled by aircraft were discussed by Super and Holroyd (1994). One method used tracer gas concentration measurements while the other was based on NCAR counter observations. Both methods were compared with the preferred, but often unavailable, approach of directly observing resulting ice particle concentrations with a laser probe. The methods were found to provide reasonable first approximations for the AgI aerosol and cloud conditions sampled by the study.

The tracking of AgI and SF₆ tracer gas with instruments on aircraft and ground vehicles was important in many of the reported studies. The sometimes maligned NCAR acoustical ice nucleus counter was shown to closely approximate AgI observations made by the "standard" CSU Cloud Simulation Laboratory (DeMott et al. 1995). Of course, the counter must be in good condition and must be maintained by someone knowledgeable in its proper operation. Several past applications used faulty NCAR counters or insufficiently trained counter operators. The three NCAR counters used during the Plateau experiments were often cross compared and found to be in good agreement.

Considerable effort was expended into calibrating and comparing fast response SF₆ detectors during the field programs. Known concentrations of the gas were injected into the detectors at frequent intervals. Like NCAR counters, these instruments also require significant maintenance and knowledgeable operators.

The CSU laboratory studies by DeMott et al. (1995) provided a new calibration of the NAWC AgI generator. It demonstrated that improvements had been made since the last calibration because warmer temperature ice particle yields were significantly enhanced. Beside the generator calibration with the standard AgI-NH₄I-acetone-water solution used in Utah, one was made with a solution also containing sodium iodide and paradichlorobenzene. This latter solution was expected to produce a condensation-freezing ice nuclei. Laboratory tests showed that ice crystal production rates were much faster with the latter solution. The results imply that an order of magnitude increase in ice crystal formation could be

obtained simply by switching seeding solutions. It is strongly recommended that such a change be made in the operational program.

Considerable development, testing, and improvement of liquid propane dispensers was accomplished during the Plateau program. These dispensers were used during many of the seeding experiments. Propane dispenser development was based on important earlier work by Reynolds (1991) in California. A totally automated propane seeding system was constructed (Super et al. 1995). An icing rate meter detected SLW at the main propane dispenser site, and that dispenser and two satellite dispensers were turned on and off as appropriate by programmed data loggers. All propane dispensers were on high exposed ridges well upwind of the main barrier. This automated system remains in operation in the mountains east of Ephraim, Utah, and a similar dispenser was recently deployed to the Wind River Range of Wyoming (Roger Hansen, personal communication).

Cripps and Abbott (1997) developed a prototype icing rate meter for possible use with propane dispensers. Ideally, each dispenser would be controlled by its own icing rate meter detecting SLW presence at the dispenser. It was hoped that more economical units could be developed, using direct current electrical power from solar panels. While initial tests were promising, additional field tests and possible modifications would be required before the device could be considered operational.

7. SUMMARY AND RECOMMENDATIONS

7.1 Overview

Summarized results of the final several years of the NOAA/Utah AMP program, conducted on central Utah's Wasatch Plateau from early 1990 through early 1996, are presented in this report. Considerable earlier work accomplished on the Tushar Mountains of southern Utah has been presented elsewhere.

The main goals of the NOAA/Utah AMP have been to investigate the effectiveness of the Utah winter operational (applied) cloud seeding program and to recommend ways to improve that program's effectiveness. Findings and recommendations have been reported to the NOAA AMP and to the Utah Division of Water Resources. The latter agency partially sponsored the operational program in cooperation with local water user groups. The operational program sponsors have the decision making authority concerning implementation of any of the suggested changes.

Findings and recommendations have been provided in various levels of detail. A less detailed overview is given within this and previous sections of this report. More detail is provided in section 8, to follow. The reader is referred to the original 29 articles and conference papers summarized in section 8 for complete discussions of the various investigations. Finally, for anyone interested in greater detail, various contractor reports and field operation plans exist which are not listed herein.

7.2 Key Physical Questions

The NOAA/Utah AMP did not pursue statistical evaluations of the operational seeding program because of the many difficulties and uncertainties involved with such analyses as referred to in section 1. Rather, the NOAA/Utah AMP used physical observations and reasoning, including sophisticated numerical modeling, to investigate the key processes involved in winter orographic cloud seeding aimed at snowfall augmentation. The key physical questions involved in evaluation of such seeding can be briefly stated as follows:

1. When, where, and in what quantities does SLW exist within orographic clouds in excess to that naturally converted to mountain snowfall?
2. When, where, and in what quantities does the seeding agent affect the SLW cloud, converting portions of it to embryonic ice particles? In Utah, the operational seeding agent has been AgI produced by valley generators using the acetone-silver iodide-ammonium iodide solution.
3. When, where, and in what quantities do the seeded ice crystals grow to snowflake sizes and fall to the mountain surfaces?

Most of the investigations reported during the NOAA/Utah AMP addressed one or more of the above questions.

7.3 Key Physical Findings

Brief answers to the above questions, based largely on the work reported herein, are now stated:

- a. A considerable body of evidence from the Plateau investigations and some other work shows that significant SLW cloud exists over western mountains in excess of that naturally converted to snowfall. This "excess" SLW flux represents a large fraction of seasonal snowfall amounts. While the existence of "excess" SLW water cloud has been assumed for decades, and is necessary for operational seeding to have any potential, adequate documentation has been provided only during the past several years. Field deployment of microwave radiometers has been especially important in this documentation.
- b. Orographic cloud SLW varies rapidly in time and space. Some of the greatest SLW amounts have been found during storms with strong synoptic support which are naturally very efficient snow producers during some phases but inefficient during other phases. Conversely, weaker localized storms typically produce lesser SLW amounts but these persist over many hours per winter. Both storm types are important in total seasonal SLW flux production.
- c. Orographic cloud SLW is usually found over the windward slopes and crests and rapidly diminishes further downwind, even as cloudy air moves across the relatively flat Plateau top, about 10 km wide. The SLW is depleted by a combination of snowfall production and subsidence of the airflow.
- d. The SLW cloud is confined to a shallow layer above the terrain. Most SLW condensate exists in the lower 500 m above the terrain and SLW amounts are usually negligible at an altitude of 1,000 m above the terrain. Forced orographic uplift, weak embedded convection, and gravity waves all combine to produce the liquid condensate.
- e. The SLW cloud found near the mountainous terrain is typically mildly supercooled over Utah's mountains. Frequently, the SLW cloud is too warm for significant ice nucleation with AgI, except perhaps in its upper portions. Often natural ice nucleation processes become efficient as cloud temperatures become cold enough for effective AgI nucleation. Consequently, the "window of opportunity" for effective AgI seeding is limited to a fraction of the periods with "excess" SLW. To restate this important point, most SLW periods cannot be effectively seeded with the present type of operationally applied AgI, especially when it is released from the ground with resulting limited vertical dispersion.
- f. The frequency of successful transport of AgI plumes over the Plateau is directly related to generator elevation relative to the mountain barrier. Plumes released from high altitude sites within 300 to 500 m of the Plateau top were routinely transported over the barrier when winds had a cross-barrier component, necessary for significant SLW production. Similar results have been demonstrated at several other mountainous locations, including Montana, Colorado, and Arizona. High altitude release sites on the Plateau were usually just below or just above cloud base.
- g. While experimental cases are limited, a definite impression developed over the course of the experiments that canyon mouth releases have a significantly greater probability of over-Plateau transport than valley releases.
- h. Plumes released from the valley floor are less likely to be transported over mountain barriers than plumes released from higher elevation sites. A number of experimental periods showed that AgI

was trapped near the valley for extended periods. However, storm periods with relatively abundant SLW over the Plateau and embedded convection present usually also had valley AgI transport to the Plateau top. But effective ice nuclei concentrations from valley-released AgI were usually quite small at prevailing cloud temperatures.

- i. On some occasions, the gravity wave mechanism transported valley-released AgI over the Plateau in spite of valley-based inversions. The timing and frequency of gravity waves, and the specific surface locations affected by them, are all uncertain, but this mechanism is sometimes important in vertical transport of the AgI aerosol.
- j. High altitude AgI generators have at least two advantages over valley-released generators in addition to their ability to routinely target the intended cloud zones. The concentrations of AgI and resulting ice particles from high altitude generators were usually much greater, as monitored along the Plateau top and above the Plateau by aircraft. The results of model simulations were in agreement with these observations. In addition, high altitude generators were usually located within cloud or just below cloud base. The AgI generators produce a large water by-product from combustion of propane and acetone. The resulting high supersaturation very near the generators allows for instantaneous activation by the condensation-freezing mechanism (Finnegan and Pitter 1988, DeMott et al. 1995). Thus, under favorable conditions, embryonic ice crystals may be formed immediately downwind of the generators, providing important additional time for growth to snowflake sizes. The condensation-freezing mechanism is unlikely to occur with valley-releases of AgI, and if ice crystals are occasionally formed because valley fog is present, they will not survive to orographic cloud altitudes.
- k. Disadvantages of high altitude AgI generators include the practical difficulties of installing and maintaining them at remote locations, and limited horizontal plume dispersion. While aerosol from high altitude generators will routinely be transported over the mountain barrier, cross-wind spacing of such generators should not exceed perhaps 5 km if most of the SLW condensate zone is to be affected. However, it may be more important to routinely seed a portion of the SLW cloud than to sometimes seed more of it, but only with weak AgI concentrations. Vertical dispersion from the high altitude generators appeared similar to that from the valley-based generators, but this impression may be partially based on the much greater INC found during aircraft sampling within high altitude released plumes. Valley-released plumes generally had weak INC at aircraft altitudes.
- l. A seeding solution different from that used in the operational seeding program was tested in the CSU laboratory. This solution produces an AgICI-0.125NaCl rather than AgI aerosol. It can nucleate ice crystals by the condensation-freezing mechanism rather than the contact nucleation mechanism by which operationally used AgI aerosol operates (in the absence of supersaturation). This fast-acting aerosol was shown to increase the number of effective seeded ice nuclei by over an order of magnitude in the limited time available for transport through orographic SLW cloud. It is strongly recommended that the operational seeding program use this improved solution. This is one of a number of actions which could increase concentrations of effective ice nuclei over Utah's mountain barriers.
- m. Numerous physical seeding experiments demonstrated that sufficiently great AgI concentrations exposed to sufficiently cold SLW cloud will produce abundant ice particles. Ice particle concentrations were similar to those expected, based on earlier laboratory results, tending to verify laboratory findings in actual orographic cloud. When obvious seeding-caused snowfall

occurred, rates were light as is typical of natural snowfalls. The heaviest hourly accumulation observed during the seeding experiments was 1 mm liquid equivalent.

- n. Propane releases at rates of 3-7 gal h⁻¹ were clearly demonstrated as capable of producing 10 to 20 ice crystal per liter even during slightly supercooled conditions. This approach offers a practical adjunct or alternative to AgI seeding during the mildly supercooled episodes typical of Utah winter orographic storms. Moreover, propane seeding was totally automated, using an icing rate meter to detect SLW cloud and a data logger to "decide" to release the liquid propane only during seedable conditions.

7.4 Summary of Findings and Recommendations

In summary, SLW, the necessary "raw material" needed for cloud seeding to be effective, is frequently present in Utah's orographic clouds. Amounts of SLW are adequate to provide the potential for artificial nucleation by cloud seeding to enhance the mountain snowfall at higher elevations. However, numerous physically-based investigations reported herein strongly suggest that the current operational seeding program is unlikely to convert much of the available SLW to additional snowfall.

The main problem with the Utah operational seeding program is that observed concentrations of effective AgI in nuclei are too low for significant snowfall enhancement from the mildly supercooled clouds. Much of the time, the entire SLW layer is too warm for effective seeding with AgI, which begins to nucleate ice crystals near -6 °C, but which is ineffective in the concentrations observed until the SLW cloud is colder than about -9 °C. Under such circumstances, a different seeding agent is needed, such as liquid propane. When colder SLW cloud does exist, the "window of opportunity" is quite narrow before natural processes produce sufficient ice particles for effective snowfall.

A number of steps aimed at increasing the operational program's effectiveness can be taken. Admittedly, most of them would increase the program's cost. However, in terms of snow enhancement, these improvements may make economic sense. It is beyond the scope of this work to provide such economic evaluations.

7.4.1 Recommendations to Improve AgI Seeding Effectiveness

If the Utah operational program is to continue to rely on AgI seeding, some of the following possible steps ought to be considered because they should improve program effectiveness.

- a. Convert to a seeding solution capable of producing an AgI aerosol that nucleates by the condensation-freezing mechanism rather than relying on the contact-freezing mechanism.
- b. Significantly increase the density of seeding generators and the ice nuclei output per generator.
- c. Place generators in canyon mouth rather than valley floor locations.
- d. Use high altitude generators located at least half way up the windward slope of the targeted mountain barriers.

- e. Use high altitude generators on barriers just upwind of the intended target barriers, such as the San Pitch Mountains in the case of the Wasatch Plateau. This approach would provide important additional time for seeded ice particles to grow and fall to the surface.
- f. Consider whether aircraft seeding can provide AgI aerosol to sufficiently cold SLW regions during relatively warm storm periods. However, aircraft seeding with AgI generators may often be impractical when the SLW is contained in a shallow, mildly supercooled layer just above the mountain barrier. That is, aircraft with attached AgI generators may not be able to safely operate at sufficiently low altitudes during many storm episodes. Dropping of AgI flares is an alternative which may be cost prohibitive when duration and volume of coverage are considered.

7.4.2 Additional Recommendations

In addition, it is recommended that automated liquid propane seeding be expanded from the three dispenser operation already in use east of Ephraim, Utah. This approach would profit from the use of direct current icing meters which could be operated in the field with solar panels and storage batteries. Available commercial models employ an alternating current heater requiring field use of an inverter. However, according to personal communication with one of their representatives, circuit changes could be made by the manufacturer. This approach should be affordable and has the several advantages previously discussed. Unlike automated AgI generators, propane dispensers are simple, reliable, and economical devices.

As a separate recommendation, numerical modeling studies should be used to determine optimum seeding locations and source strengths of both AgI generators and liquid propane dispensers. The Clark model has been shown to produce reasonable simulations of SLW cloud and AgI aerosol transport. The model is set up on a workstation and simulations can be produced at limit cost. The model should be run with various seeding configurations and under the range of storm conditions found in Utah. An abundance of sounding observations already exists for model initiation. Such modeling investigations should lead to improved AgI generator and propane dispenser placement. Reasonable estimates could be made of the AgI ice nuclei production and propane ice crystal production needed to affect the range of SLW cloud temperatures typically found over Utah's mountains.

Finally, it is strongly recommended that any future evaluations of the Utah operational program, whether statistically or physically based, be conducted by totally disinterested parties. This would add objectivity and credibility to the evaluations. In fact, it is recommended that any meteorologists or statisticians tasked with such evaluations should have had no prior involvement in the Utah operational or experimental programs, or any financial stake in the operational program. Anyone with prior involvement likely already has firm opinions about the operational program's effectiveness. These opinions might inject bias into future evaluations as might any financial interest.

8. SELECTED PORTIONS OF THE 29 ARTICLES AND CONFERENCE PAPERS

The following articles and conference papers are listed alphabetically within each year. The years listed are from 1992 through 1998. In general, the following was directly extracted from each paper: author(s), title and publication, abstract and/or introduction section, and summary and/or conclusions/recommendations sections.

1992 articles and papers:

8.1. Heimbach, J. A., Jr., and A. B. Super, 1992: *The number of experimental units required to achieve a statistical significance with different seeding responses in a winter orographic experiment. Symposium on Planned and Inadvertent Weather Modification, Atlanta, GA, American Meteorological Society, 132-135.*

INTRODUCTION

Several investigators have used Monte Carlo techniques to investigate the number of experimental units needed to achieve statistical significance in simulated cloud seeding experiments. For examples, see Schickedanz and Decker (1969), Heimbach and Super (1980) and Medina and Rasmussen (1989). A common approach is to randomly choose experimental units (storms, days, etc.) from a non-treated population. Another random decision determines whether each unit's response variable is modified by a "treatment" or is left untreated. The treatment usually is a fixed percentage change to the natural observation. As additional experimental units are selected and treated or not, the two subpopulations are repeatedly tested for the null hypothesis. (The use of a nonparameterized statistical test eliminates assumptions about the distribution of the observations). This procedure is continued until the null hypothesis is refuted at a desired level of significance, α , after a total number of experimental units, N , have been chosen. The value of α is typically specified at 0.05, indicating a 5% probability of concluding there is a seeding effect when none exists (a Type I statistical error).

The same randomized procedure is repeated many times to estimate the β levels from the resulting distribution of N values. β is the probability of concluding no seeding effect exists when one is actually present (Type II statistical error). For example, if 1000 simulations are run and 900 of them show the required α -level within N , experimental units or less, then the β -level is estimated as 0.1 for an experiment that obtains N units. The power of the test is $1 - \beta$.

Observations of supercooled liquid water (SLW) from storm to storm and during individual storms have indicated significant variability (Raubert et al., 1986; Super and Holroyd, 1990). It is also likely that effective ice nuclei concentrations in the SLW zone vary markedly with changes in silver iodide (AgI) generator output related to wind speed, atmospheric stability, airflow interactions with local topography, temperature of the liquid cloud and other factors. The combination of variations in SLW and in effective ice nuclei concentration, as well as other factors, should result in large differences in seeding responses. The question of winter orographic cloud seeding effectiveness still is an open one (AMS, 1985) although several statistical evaluations have indicated net snowfall increases of about 10-15%. For example, the Bridger Range Experiment (BRE) conducted in southwestern Montana suggested approximately 15% seasonal snowfall increases by evaluation of both snow course and precipitation gauge data, according to the post hoc exploratory evaluation of 24 h periods by Super and Heimbach (1983). However, their analysis indicated that seeding effects were confined to the colder storms. The mean double ratio

suggested a 56% of snowfall increase for the seeded storms when the temperatures on the main ridge were -9°C or colder. Later physical observations (Super and Heimbach, 1988) lent credibility to the statistical findings. Further exploratory analysis by Super (1986), limited to 6 h periods with main ridge temperatures of -9°C and colder suggested that, "the seeding method used was highly effective during a small portion of all seeded episodes, but had little or no effect for the other periods". It is noteworthy that a double ratio of 2.22 (122% increase) was calculated by Super (1986) for the warm cloud top partition. This suggests that large increases may be realistic for particularly seedable cases and these are responsible for most of the seasonal increase detected. If the above statistical indications approximate reality, the apparent seasonal snowfall increases of about 15% in the BRE were due to large percentage increases from a small fraction of all units, and little or no increases (or decreases) from all the rest. No evidence of decreased snowfall due to seeding was found.

SUMMARY AND CONCLUSIONS

The purpose of this paper is to examine how the duration of a statistical winter orographic cloud seeding experiment might vary with different assumed responses. Several previous investigations using Monte Carlo simulations have assumed that each treated experimental unit (case) has the same percentage response. There is increasing evidence that this simple model is unrealistic. It seems more likely that seeding results in large percentage increases from a fraction of cases that are particularly amenable to treatment, but has little or no effect on the remainder.

Monte Carlo techniques were applied to nonseeded 6 h data blocks from the Bridger Range Experiment in the simulated experiments. For simplicity, only the probability levels $\alpha = 0.05$ and $\beta = 0.1$ were run. Following the results of the exploratory statistical analysis of Super (1986) for the cold partition, a net precipitation increase of 66% was approximated in each experiment. However, this increase was achieved by six different assumed responses to seeding. First, it was assumed that each "seeded" case resulted in a 66% precipitation increase. Second, only half the cases randomly chosen to be "seeded" had their precipitation increased, but by 132% ($2 \times 66\%$). Similar procedures were followed until the final simulation provided increases for only 1/6 of the "seeded" cases, but each was given an increased of 396% ($6 \times 66\%$). These simulations were calculated for both a "cold" partition (all available cases with main ridge temperatures of -9°C and colder) and a "warm" partition (all cases colder than 0°C).

It was found that the number of units required to achieve statistical significance varied considerably with the different seeding effects. For the cold partition only about one winter season would be required if each "seeded" case resulted in the assumed 66% increase. However, over 5 winters would be required if the same net increase resulted from 396% increases applied to 1/6 of the "seeded" cases.

As might be expected, less time would be required if both the warm and cold cases could be successfully treated, because of the large increase in available cases each winter. However, this was partially offset by the increased variability associated with the warmer cases.

The implications of these results are sobering. It may be that the number of experimental units required to achieve given α and β levels is far larger than estimated for a number of past experiments. This could partially explain the frequent finding of inconclusive results.

A number of points need to be considered in designing future statistical experiments. First, strong predictor-covariate relationships with target area precipitation are necessary to reduce the cases needed to detect a seeding signal. Similarly, partitioning based on a good physical understanding is necessary to reduce the number of experimental units that have minimal response to seeding. Third, improved

statistical techniques could be very useful, but their development may be difficult in view of uncertainties of just how seeding responses vary among the population of treated units. Fourth, and most important, a much improved physical understanding is needed prior to development of any future statistical design. A decade ago Braham (1981) made a strong case for improving our physical understanding before conducting any further "black box" experiments that have a major emphasis on demonstrating precipitation changes at the ground. His advice is as valid today.

8.2. Huggins, Arlen W., 1992: Mapping Supercooled Liquid Water with a Mobile Radiometer. Symposium on Planned and Inadvertent Weather Modification, Atlanta, GA, American Meteorological Society, 102-107.

INTRODUCTION

Throughout the 1980's, and continuing into the early 1990's, ground-based microwave radiometers have been used on numerous wintertime weather modification projects to verify the presence of supercooled liquid water (SLW) in orographic clouds that have been the target of cloud seeding experiments or operations. Although the instrument is transportable, in the past radiometers have been stationary during data collection periods.

During the Sierra Cooperative Pilot Project (Reynolds and Dennis, 1986) a dual-frequency radiometer was positioned at several different locations on the windward side of the Sierra Nevada, but for the final four winter field seasons the instrument was operated in a zenith-pointing mode near the main Sierra Nevada crest. The reasoning was that, from this vantage point, the radiometer would detect cloud liquid that was passing over the crest and not entering into the precipitation process. The SLW measured above the crest location was, therefore, considered an estimate of the amount that might be tapped by an appropriate cloud seeding technology. Heggli and Rauber (1988) summarize SLW occurrence at the crest site for different types of storms.

Winter storm research studies in the mountains of Utah have taken advantage of the scanning capability of ground-based radiometers. Rauber and Grant (1987) show the temporal evolution of SLW over the upwind edge of the Tushar Mountains using data from a radiometer located at the base of the mountains, which was scanned at an elevation angle of 20 degrees. They were able to detect azimuthal variations in liquid amounts which were related to local topographic features. Sassen et al. (1990) used a midbarrier of the same mountain range to clearly delineate the orographic stages of winter storms and further describe topographic influences. In both cases, because of the relative shallowness of the liquid layers and the steepness of the antenna elevation angle (>20 degrees), the radiometer measured microwave emission from clouds only a few kilometers from the instrument site, and thus detected only very localized spatial differences.

In a final example of stationary radiometer applications, Huggins et al. (1990) describe the evolution of SLW from two locations using two radiometers. They documented differences in cloud liquid that occurred over a mountain crest compared to a downwind valley for various winter storms stages, and during the passage of mesoscale cloud bands. This study revealed the potential for using multiple radiometers to study the water budget of winter storms by measuring the development or depletion of cloud liquid as a function of mountain barrier position.

During the 1991 Atmospheric Modification Research Program conducted cooperatively by the state of Utah and the National Oceanic and Atmospheric Administration (NOAA), a new technique of mobile

radiometer data collection was tested. The experiments took advantage of the mobility of one radiometer, as well as the measurements of two radiometers, to more completely describe the spatial and temporal evolution of SLW in winter storms over mountainous terrain. The barrier under study was a relatively isolated plateau which had roads open during the winter to allow crossing the barrier by vehicle.

A variety of storm situations were studied, but it was thought beforehand that the orographic stage of a storm, in the absence of mesoscale bands, would be most conducive to study with a mobile platform since the cloud field might be relatively steady-state, and fixed in position. In this situation the mobile radiometer was used to develop a profile of liquid depth as a function of position over the windward slope. Multiple traverses were made to determine the variability of the cloud field. In the presence of mesoscale cloud bands the intention was to monitor the liquid amounts in the band over the windward slope using the mobile radiometer, while the stationary radiometer measured the liquid remaining in the band at the top of the mountain barrier. The mobile radiometer was also used to determine if cloud liquid varied, in a persistent manner, across the top of the plateau, or along the upwind edge of the plateau. Selective stationary positioning of the mobile radiometer allowed for a variety of upwind/downwind comparisons between the two radiometers.

The mobile radiometer will be shown to have an advantage in following the changing spatial characteristics of a mountain cloud system. In addition the mobile system is shown to offer a better means of describing topographic influences by providing measurements over a scale generally greater than that obtained by radiometer scans. The two-radiometer system is covered in one example, and this technique suggests an improvement over the evaluation of a cloud system by one unit, in that both upwind and downwind liquid evolution can be simultaneously monitored.

SUMMARY AND DISCUSSION OF RESULTS

A new technique for studying the spatial characteristics of supercooled liquid water in winter storms over mountainous terrain has been described. The examples presented focused on mainly on measuring the location of liquid water relative to the terrain on the windward slope of the Plateau. Past studies of supercooled liquid water in the mountains of Utah and elsewhere in the western United States have documented the temporal variability of liquid from storm to storm and on a smaller scale within the same storm. In a few cases, radiometer scan data have been used to determine the spatial variability of SLW (Sassen et al., 1990). Mesoscale phenomena have been shown to sometimes produce a periodic variability in cloud liquid (Sassen et al. 1990). For these reasons the mobile experiments on the windward slope (Route 1) during this first year of experimentation, were repeated as often as possible (52 traverses during the 2-month project) to document the spatial variability of SLW more completely. At least one prior study (Heggli et al. 1983) used several seasons of aircraft data to document the spatial characteristics of SLW over the windward slope of the Sierra Nevada. The limitation with aircraft is the inability to detect SLW close to the terrain, where other studies (e.g. Heggli and Rauber, 1988) have shown that the bulk of SLW exists. Unaffected by this limitation, the complete mobile radiometer data set should provide a much more accurate representation of the distribution of SLW relative to terrain.

A description of four mobile radiometer experiments from three different winter storm periods was provided. This represents only a small fraction of the experiments conducted during at least 10 storm periods during the 1991 Utah/NOAA field program, but some interesting results were obtained. The modified DRJ mobile platform proved to be capable of measuring liquid and vapor depth. The measurements were made at times under adverse weather and road conditions, but data loss was probably no worse than when a radiometer is operating in a stationary mode. Some extreme situations with very poor visibility were avoided.

Liquid water variability above the mountainous terrain was expected and indeed was observed as sequential traverses over the same route often produced different spatial profiles of liquid water. However, there was consistency in the location of liquid water maxima over midbarrier on the windward slope. There was also consistency in the observation of smaller liquid depths above the top of the Plateau compared to regions above the windward slope. This appeared to be primarily due to removal of SLW by precipitation but a localized terrain effect at midbarrier might also have contributed to the result. One experiment also suggested that the lower liquid values over the DOT site might have been caused by its location on the downwind side of a local ridge. Analysis of additional cases will be needed to confirm this.

The mobile radiometer provided important information on the location of the upwind edge of liquid cloud. In one neutrally stable situation cloud edge remained fairly constant over a few hours, while during an unstable case the upwind liquid cloud edge changed markedly. Obviously, propagating mesoscale phenomena can affect the location of liquid over a barrier. Satellite images and the project radar data will be used to confirm the presence of such features. The location of cloud liquid and its quantitative spatial characteristics should prove useful to the efforts in modeling the cloud over this particular mountain barrier.

A two-radiometer measurement approach was briefly discussed. One case appeared to verify the depletion of cloud water by precipitation processes. With appropriate wind measurements, the two-radiometer systems could potentially provide quantitative estimates of changes in liquid water fluxes across various portions of a mountain barrier. The mobility of one or more of the radiometers allows for study of different portions of a barrier without concern for power being available at all the sites of interest. In a future field effort, the Utah/NOAA program intends to focus more on measuring the changes in supercooled liquid water across the Wasatch Plateau both during natural storm conditions and when upwind cloud seeding operations are targeting the cloud over the Plateau. One future experiment is also aimed at combining a ground-based mobile ice particle/ice nuclei measurement system with mobile radiometric measurements to attempt to document microphysical and liquid water changes across the boundary of a seeding plume. The mobile radiometer platform allows for much more flexibility in the design of experiments to either assess the potential for water augmentation by cloud seeding, or to document changes, or lack of changes, in cloud liquid during seeding operations.

8.3. Griffith, D. A., G. W. Wilkerson, W. J. Hauze, and D. A. Risch, 1992: Observations of ground released sulfur hexafluoride tracer gas plumes in two Utah Winter storms. J. Weather Modification, 24, 49-65.

ABSTRACT

Research was conducted for a two month period over the Wasatch Plateau of Central Utah during the winter of 1990-91. A portion of this research was devoted to tracking sulfur hexafluoride (SF_6) released from various ground based locations during winter storms. A NOAA King Air research aircraft was the primary mode of tracking the SF_6 . Seven flights were conducted under IFR conditions when SF_6 was released from a foothill or valley location. SF_6 was detected on six of these flights. Information on SF_6 plume widths, concentrations, vertical extent, and estimated numbers of ice crystals that would be possible if a silver iodide generator had been operated from the SF_6 release site are provided for two of these flights.

DISCUSSION (latter portion of)

The SF_6 was transported over the Wasatch Plateau in these two cases with light surface winds observed in the upwind valley and at different locations on the windward slope. The SF_6 plumes reached temperatures levels considered to be effective for silver iodide nucleation in both cases (-12 and -17°C). Some of the SF_6 plumes co-existed with low to moderate values of supercooled liquid water, another ingredient necessary for the production of a seeding effect.

Examination of the individual stacked plots for the March 2 test case indicated that the SF_6 was frequently present in regions of supercooled liquid water. These regions appeared to be associated with upward vertical motion. It is therefore concluded that these regions were associated with convection. The SF_6 plumes were observed at 1500-1800 m above the Wasatch Plateau. Based upon observed SF_6 concentrations, it is probable that these plumes reached higher altitudes. Table 4 indicates that the estimated cloud tops on March 2 were at 4 km. The plumes would have only needed to rise 250 m to reach the estimated cloud tops. Estimated cloud top temperatures were -14°C . Silver iodide had it been co-released from the SF_6 site, could have produced more ice crystals than the calculated 27 crystals l^{-1} if it was transported to the estimated cloud top heights.

The March 6 test case was much colder than that of March 2. It was also a much weaker storm system producing only a few hundredths inch precipitation on the plateau. Aircraft observations of supercooled liquid water were either 0 or occasionally .10 to .20 g m^{-3} . The Bureau radiometer at the UDOT site only observed a minimal amount of supercooled liquid water from 1600 - 1700 MST. The Desert Research Institute's mobile radiometer was operated along the Wasatch Plateau and also up and down Fairview Canyon. This mobile radiometer detected very little supercooled liquid water on this day except for a brief period from 1713 to 1728 MST. The mobile radiometer was driving down Fairview Canyon during this time. Liquid water values varied from .03 to .17 mm during this time. The Bureau radiometer on UDOT did not report any liquid water during this period. This period could have represented some seeding potential. This period was, in fact, being seeded from the valley based ground generator network as evidenced by NCAR counts considerably above background (several 10's of counts per minute). The cold ambient temperatures at which the silver iodide nuclei resided should have resulted in nucleation whenever the nuclei encountered any supercooled water droplets. The angles of dispersion (the last column in Tables 4 and 5) from the SF_6 ground based release point to the aircraft flight tracks ranged from 4 to 46° . An average of the angles from the four SF_6 plume encounters in March 2 on the west track was 35 degrees. A similar average for the eight encounters on the west track for March 6 was 17 degrees. Most of the difference between the two days averages occurred due to a very wide SF_6 plume being encountered on the first two western flight legs on March 2 (40 and 46 degrees). It does not appear there is still more lateral dispersion of the SF_6 on the March 2 versus March 6 case. The difference could be due to much stronger convection that was encountered on March 6. An average plume spread angle for the two days on the western flight track was 23 degrees.

One important question that is not answered by this data set is whether multiple SF_6 releases from the valley generator network would merge over the Wasatch Plateau to form a relatively continuous "treated" volume. The NCAR counter data may provide some information on this question, but the lag time and flushing time of this instrument complicates such an analysis. A related question is, even if SF_6 and/or AgI is released at multiple valley sites, do the resultant plumes disperse in a relatively uniform fashion over the Wasatch Plateau, or are they channeled up some of the canyons as these test cases might suggest?

It is assumed that there is a uniform horizontal dispersion of AgI from the valley generators over the Wasatch Plateau, the mean SF_6 plume angle of 23 degrees can be used to estimate a desired spacing between the valley generators. The mean distance from the ground based silver iodide generators sites to

the western flight track is 10 km. In order for the plumes released from the valley to be continuous over the west track would require a generator spacing of 4.4 km based on an average dispersion angle of 23 degrees. The spacing utilized in the conduct of the Utah operational seeding program is approximately 16 km. The spacing of the eight generators utilized in the conduct of this research program was approximately 5-10 km. Both the spacing on the operational and research program would appear to be too sparse on the basis of these calculations. Future research needs to address this question in more detail. The authors believe the best way to gain quantitative information on this question is through multiple valley releases of SF_6 . Co-location of SF_6 releases with silver iodide releases would also be very beneficial. This would allow an analysis of ice crystals concentrations and sizes within and outside SF_6 plumes. These SF_6 plumes would be used to precisely "tag" the location of the silver iodide seeding material made possible by the very fast response time of the real-time SF_6 analyzer.

It is difficult to assess how representative the results from this two month research program may be of the climatology of Utah winter storms. Both of the test cases discussed in this paper was post-frontal. Post-frontal conditions in Utah in winter are frequently more convective than pre-frontal. The presence of convection may be important in the vertical dispersion of ground released seeding material.

It is concluded from this discussion that in these two test cases, silver iodide could have been transported from a release site at the mouth of Birch Creek Canyon into environmental conditions that would lead to nucleation. NCAR counter observations provide independent confirmation of the transport of silver iodide nuclei, released from the valley floor, over the Wasatch Plateau.

8.4. Super, A. B., and A. W. Huggins, 1992a: Investigations of the targeting of ground-released silver iodide in Utah, Part I: Ground observations of silver-in-snow and ice nuclei. J. Weather Modification, 24, 19-33.

ABSTRACT

During the winter of 1989-90, the Utah Division of Water Resources, the National Oceanic and Atmospheric Administration, and the Bureau of Reclamation cooperated in a limited sampling project to investigate the transport and dispersion of silver iodide (AgI) cloud-seeding aerosol over two target areas in the mountains of Utah. Seeding was done using the ground-based AgI generator network of the Utah operational cloud seeding program. Transport and dispersion over the Wasatch Range and Wasatch Plateau were evaluated using a silver-in-snow sampling technique and the real-time detection of AgI aerosol and sulfur hexafluoride gas.

This report contains an extensive review of past silver-in-snow results from several different regions as a basis for comparison with the current study. The 1989-90 Utah results indicated that a low percentage (<15 percent) of bulk snow samples from 10 mountain target area locations had silver (Ag) concentrations above values for periods when seeding had been conducted. Consistently poor targeting and/or low seeding generator output could explain the general lack of detectable Ag in the two Utah target areas.

Seeding generator output also forms the basis for estimates of average ice particle masses required to achieve the greater than 11 percent snowfall increase reported from statistical analyses of the Utah operational program. These estimates are based on very optimistic assumptions (perfect targeting, 100 percent nucleation, 100 percent fallout, etc.) They indicated that snowfall enhancements of 10 percent or greater are unlikely with the current AgI seeding rate of 6 grams per hour used in Utah.

Real-time detection of ground-released AgI showed that seeding material was routinely transported up a particular canyon when releases were made near the bottom of the canyon. Concentrations of AgI at the up-canyon observations site (adjusted for nucleation activity at -10°C) were, however, estimated to average only about one ice nucleus per liter. This relatively low concentration of active AgI nuclei offers a partial explanation of the observed low percentage of silver-in-snow above background at sampling sites above the canyons where AgI was released.

SUMMARY

Silver-in snow analyses and detection of ice nuclei during the Utah/NOAA winter field program in 1989-90 have produced some insights into the transport and dispersion of AgI aerosols over two of Utah's operational cloud seeding target areas. Because of the lack of accompanying detailed meteorological and cloud microphysical data, a complete explanation of the results found during this limited field effort will require further study.

The results of the silver-in snow investigations at sites in the Wasatch Range and Wasatch Plateau revealed that background (nonseeded) Ag concentrations were similar to those found by Long (1984) in the Tushar Mountains of southern Utah. In addition, as Long found in Ag samples from 1983, there was little evidence of enhanced Ag concentration in snow samples from seeded periods.

Possible explanations for the low frequency of above-background Ag are:

- 1) consistently poor targeting of the AgI occurred from the predominantly valley-based generators to the high altitude target areas located east (presumably downwind) of the generators,
- 2) the 6 g h^{-1} AgI output of the Utah operational generators was not sufficient to produce enhanced Ag concentrations, even if targeting was good.

A comparison with the results of the Bridger Range experiments, where seeded snow samples consistently contained enhanced Ag and where good targeting existed, supports the explanation that generator output could account for the different Ag concentration in seeded samples. The mean monthly Bridger AgI generator output exceeded Utah generator output by a factor of 20, while the Ag concentration in seeded snow samples in the Montana experiment exceeded Utah samples by factors of 10-30. However, given the relatively short periods represented by Utah samples (1-14 days compared to Bridger seasonal data), one would expect a larger percentage of "hits" than was observed in the Utah target areas. The low frequency of the above-background Ag concentrations brings into questions whether routine targeting was accomplished. Part II of this paper will address this question in more detail as will the more comprehensive transport and dispersion studies performed in the 1991 Utah/NOAA program, yet to be fully analyzed.

The question of seeding generator output was also addressed in the context of 11.4 percent precipitation increases for the Utah operational program suggested by statistical analysis of precipitation data (Griffith et al. 1991). A number of optimistic assumptions were employed such as a generator effectiveness of 5×10^{12} ice nuclei per gram of AgI for the SAW zone, perfect targeting by the valley-based generators, nucleation by all potentially active AgI particles, and growth and fallout of all nucleated ice crystals onto the targets. Using these assumptions, an estimate was made of the average ice particle mass required to produce the reported precipitation increases. The average computed masses of 0.07 to 0.23 mg were much larger than typical average masses of natural snow particles documented in several locations in the western United States. It is possible (but believed unlikely) that generated ice nucleus effectiveness in

natural clouds is substantially greater than that found in cloud chambers. It is also possible (but believed unlikely) that some form of ice multiplication routinely creates an order of magnitude or more additional ice particles without further nucleation by AgI. Unless such mechanisms are involved, the calculations strongly suggest that the current network of Utah generators cannot produce snowfall enhancements approaching 10 percent with the type of seeding solutions used and an AgI release rate of 6 g h^{-1} .

The real-time sampling of AgI and SF_6 in one canyon several miles above two seeding generators produced puzzling results. AgI was detected in every instance when generators were operated near the bottom of the canyon, yet snow samples immediately above the head of this canyon rarely yielded enhanced Ag concentrations. This result might be partially due to low AgI concentrations. When the mean IN concentration from the acoustical counter (operated at -20°C) was reduced to account for decreased effectiveness at a more typical liquid water temperature of 10°C , the IN concentration dropped near 1 IN per liter. At this low concentration, seeding would probably not significantly increase snowfall, nor would enhanced Ag be detected in the snow downwind. One special experiment using a fast response SF_6 detector in the canyon supported this low concentration explanation. At the altitudes and temperatures where the gas was detected the corresponding AgI concentrations (estimated from SF_6 concentration) would have been very low. Nucleation at concentrations of about 10 IN l^{-1} would likely have occurred only at higher (colder) above crest line altitudes. If these canyon conditions were typical of most storms, the lack of Ag in snow just above the canyon head is not surprising.

Most winter cloud seeding projects have only assumed, but not tested, the adequacy of their targeting. Physical evidence continues to accumulate that routine targeting of adequate IN concentrations to SAW regions may be the exception and not the rule. It is strongly recommended that projects which have not done so, carefully scrutinize their targeting. We cannot claim to have a credible technology unless we demonstrate that our seeding methods actually treat the clouds.

8.5. Super, A. B., and A. W. Huggins, 1992b: *Investigations of the targeting of ground-released silver iodide in Utah. Part II: Aircraft observations. J. Weather Modification*, 24, 35-48.

ABSTRACT

As part of a cooperative research program between the Utah Division of Water Resources, the National Oceanic and Atmospheric Administration, and the Bureau of Reclamation, a series of aircraft missions was flown to track silver iodide plumes in the Utah operational cloud seeding program. Both valley floor and canyon mouth generator sites were tested using releases of sulfur hexafluoride tracer gas and silver iodide. Optically-tracked Airsondes provided supporting wind and stability data. Five missions were flown under atmospheric conditions that either simulated, or were the beginning of, the prefrontal phase of typical Utah winter storms. The silver iodide and tracer gas were confined to the lower atmosphere during four flights and were not transported over the intended mountain barriers. The plumes did cross the Wasatch Plateau during part of the fifth sampling mission. Ice nucleus concentrations were estimated from the tracer gas measurements of the fifth mission for typical supercooled liquid water temperatures. These estimates indicated that limited ice crystal concentrations would be formed with the generators and seeding agent currently used in Utah.

SUMMARY

A series of five aircraft missions tracked AgI and SF₆ (simulated AgI releases) from valley and canyon mouth sites used in the Utah operational seeding program. All flights took place in VFR conditions to permit very low-level sampling over both mountainous terrain and within valleys. Each mission was flown under atmospheric conditions typical of prefrontal conditions during winter storms. In fact, snowfall was occurring at higher elevations during some sampling flights.

Four of the five aircraft missions found that real and simulated seeding material was transported along the mountain barrier rather than over it, or the material was trapped by low-level stability and was drifting about the valley.

The AgI and SF₆ were tracked over the Wasatch Plateau during part of one mission when the lower atmosphere likely had neutral stability. Ice nucleus concentrations were estimated based on the largest mean SF₆ amount above the Plateau and the characteristics of the AgI generators used in Utah. It was found that ice nucleus concentrations would be very limited at typical SLW temperatures in the prefrontal storm phase. Acoustical counter measurements of IN supported this conclusion. Thus, even in the single case where plumes were transported in the layer over the Plateau where SLW is known to concentrate, resulting IN concentrations appear inadequate for effective seeding.

The present seeding approach may be effective during other storm conditions than those sampled. For example, the AgI may pool in the valleys for extended period and then be transported into the SLW region in higher concentrations during frontal passage, a possibility that has not been adequately tested. Unpublished observations from early March 1991 showed that storms with embedded convection transported valley-released AgI to aircraft sampling levels well above the Plateau. It will be interesting to analyze the resulting ice nucleus concentrations.

The observations presented in this paper, together with those described in the Part I companion paper, strongly suggest frequent ineffectiveness in current cloud seeding methods in Utah. Steps should be taken to improve the frequency of targeting of the SLW region with AgI and to increase the concentration of seeded crystals when the SLW region is targeted. The technology exists to do both.

Repeating the strong recommendation made in Part I: winter orographic cloud seeding projects should follow Utah's example and physically examine their targeting if they have not done so already. This question is too important to ignore.

1993 articles and papers:

8.6. Sassen, K., and H. Zhao, 1993: Supercooled liquid water clouds in Utah winter mountain storms: cloud-seeding implications of a remote-sensing dataset. *J. Applied Meteorology*, 32, 1548-1558.

ABSTRACT

A polarization lidar, dual-wavelength microwave radiometer, and radiosonde dataset from 19 winter storms studied over the Tushar Mountains in the 1985 and 1987 Utah-NOAA cooperative weather modification field campaigns are used to characterize embedded supercooled liquid water (SLW) clouds. The findings show the dominance of barrier-level, mildly supercooled (0 ° to -10 °C) orographic clouds, as identified by the lidar from a midbarrier field site. The combined lidar and radiometer (with liquid

water depths greater than or equal to 0.05 mm) data sample indicates an SLW cloud frequency of occurrence of about 73% of the time the lidar was operating, although only 51% of the lidar shots detected SLW clouds because of the frequent presence of range limiting attenuation from snowfall. A significant development from this study is the application of a new autonomous computer algorithm for identifying SLW clouds from single normalized lidar shots, using only the height derivative of the returned signal and the minimum linear depolarization ratio. In terms of operational AgI cloud-seeding practices, we conclude that it is mainly the upper portions of SLW clouds with relatively warm cloud-base temperatures (≥ -7 °C) that display potential for yielding increased snowfall, since only these clouds regularly produced significant (≥ 0.15 mm) radiometric liquid water depths.

CONCLUSIONS

The University of Utah Mobile Polarization Lidar has participated in several Utah-NOAA cooperative weather modification field campaigns with the primary goal of identifying the heights of SLW clouds embedded in the winter storms over the Tushar Mountains. With this knowledge and a large amount of supporting *in situ* and remote sensing data, previous basic research using case study analyses have illuminated important connections between orography, SLW clouds, and precipitation (Sassen et al., 1986, 1990). In this study, we have examined the climatological properties of lidar-detected SLW clouds for the applied research objective of assessing the general seedability (using AgI-compounds) of Southern Utah winter mountain storms and have concluded that there appears to be only a limited "window" for success involving mainly the upper portions of the relatively warm (greater than -7 °C cloud base temperature) SLW clouds containing significant (≥ 0.15 mm) LW depths. In other words, cloud layers with inferred cloud-top temperatures of colder than about -12 °C in this region appear to be efficient users of orographically generated SLW.

We have found that the total of liquid-dominated and mixed-phase SLW clouds detected by the lidar with the radiometrically detected ($LW \geq 0.05$ mm) liquid clouds comprises approximately 75% of the lidar dataset. The SLW cloud-base heights during snowfall were most frequently observed within about 0.5 km of the 2.57 km midbarrier field site. In comparison with the considerably more limited study from the 1983 field campaign (Sassen, 1985), these statistics differ somewhat. The previous study found a bimodal distribution of SLW cloud-base heights with peaks at 3.0 and 4.5 km, and the combined lidar and radiometer SLW frequency was 96%. However, the 1983 Tushar Mountain dataset, collected from a western mountain-based site (1.89 km) included only nonprecipitating or lightly precipitating storm stages. This probably accounts for the number of layers previously noted at approximately 4.5 km, presumably in the form of prefrontal altocumulus layers that did not produce snowfall. The SLW cloud height maximum at 3.0 km, on the other hand, corresponds to an upwind part of the dominant orographic SLW cloud type noted here to prevail at the midbarrier. Similarly, although the combined 96% SLW frequency from 1983 data may reflect a bias from the absence of snowfall attention effects, it is possible in view of threshold LW depth uncertainties that a frequency of as high as 90% could have been present during the 1985 and 1987 studies (i.e., using a $LW > 0$ threshold.)

One finding from the current study that deserves elaboration relates to the angular LW depth distributions given in fig 8. In agreement with a similar analysis in Sassen et al. (1990), which indicated a rather intimate association of nearby topographical features with the SLW distribution in just above-ground-level orographic clouds, our averaged spatial LW distributions tend to display localized concentrations where low-level flow is forced to ascend over steep topographical features aligned perpendicular to the wind direction. Thus, in a fairly linear, isolated barrier displaying complex terrain, as with the Tushar Mountains, SLW concentrations could be found at many locations, depending on the wind direction. According to this view, the concept of cross-barrier wind speed as a cloud seeding criterion has limited

meaning except with regard to the locations of the SLW cloud measurements and seeding material source. For the Merchant Valley measurements, for example, although no SLW clouds were detected during easterly flow (amounting to negative cross-barrier velocities), observations conducted from the eastern Tushar Mountains would likely have encountered SLW under such conditions.

Finally, whereas our earlier SLW cloud discriminations were based on a manual inspection of a sequence of polarization lidar returns, we have now developed computer-based criteria for the autonomous identification of water-dominated cloud layers on a shot-by-shot basis. Although it is true that at this early stage we manually filtered the algorithm-determined dataset to collaborate the results and identify mixed-phase clouds and very low-level (less than 200 m above surface) SLW layers (both conditions still defying autonomous identification due to oriented plate crystal and lidar beamwidth crossover effects), our visual shot inspection produced an "error" of only a few percent of the total shots. This finding is quite encouraging in that it provides the foundation for the automated analysis of lidar returns under multiphase cloud conditions, the worst-case scenario for lidar studies. Such methods are of fundamental importance to various climate research programs designed to characterize the cloudy atmosphere using lidar and other remote sensor measurements.

8.7. Super, A. B., 1993: *Precipitation gauge testing on the Wasatch Plateau, Utah during early 1993. Bureau of Reclamation Research Report R-93-17, Denver, CO, 10 pp.*

INTRODUCTION

Field Observations were made to test an ETI (Electronic Techniques, Inc.) precipitation gauge at the High Altitude Site on the western slope of the Wasatch Plateau in Central Utah, east of Fairview. The ETI gauge should require little servicing because it is designed to automatically discharge its precipitation and antifreeze mix when gauge capacity is reached. The gauge then automatically recharges itself with antifreeze. It provides digitized data at a resolution of 0.01 in., which can be transmitted from remote locations. The ETI gauge could provide a desirable alternative to conventional recording gauges in several applications, including evaluation of cloud seeding projects, if it performs as advertised. The testing program was intended to determine its performance in a winter mountain environment.

The tests were conducted in a small clearing within a conifer forest at latitude 39°, 37', longitude 111°, 22' elevation 8200 ft. The site is rated "over-protected" because of the close proximity of trees of an estimated height near 70 ft. all around the clearing. However, the site was convenient to service while testing other instrumentation in a nearby open area, and was satisfactory for comparison of precipitation gauges and snowboards.

The test period ran from 1400 (all times m.s.t.) on February 16, 1993, until 1000 on March 28, 1993. Data collected earlier have not been analyzed because the Alter windshield on the Belfort weighing gauge was several inches too high until the stated start time. That height may have been important in the very protected clearing, but adequate data exist after the shield top was adjusted to be near level with the gauge orifice top.

CONCLUSIONS

The ETI precipitation gauge proved to be reliable and provided good quality data. The only problem was an occasional tendency for the gauge to falsely indicated minor snowfall amounts, usually 0.01 in. snow

water equivalent, during relatively warm midday periods. This problem is suspected to be caused by inadequate compensation of the load cell's temperature dependence. Otherwise, the gauge compared very well with a nearby calibrated Belfort weighing gauge. If one ignores the hours when the ETI gauge indicated precipitation but the Belfort did not, the total accumulation by the two gauges was very similar. The two gauges rarely differed in hourly precipitation amount by more than 0.015 in.

Agreement between the two gauges was better than between either gauge and a nearby snowbird. Although the snowboard observations were highly correlated with both gauges, the snowboard received from 6 to 9 pct more snowfall than the gauges over the test period. Part of this difference may have been caused by gauge undercatch, although wind speeds were very limited during snowfall in the protected test clearing. It is speculated that part of the difference may have been caused by downhill drifting of snow onto the snowboard between some storms.

The observations indicated that either the ETI or Belfort gauge can provide accurate precipitation measurements when protected from significant wind. The ETI gauge has the advantages of requiring infrequent servicing and providing digital, computer-compatible data without laborious manual chart reading.

8.8. Super, A. B., and A. W. Huggins, 1993: *Relationships between storm total supercooled liquid water flux and precipitation on four mountain barriers. J. Weather Modification, 25, 82-92.*

ABSTRACT

There is a commonly held view that large winter orographic storms tend to be efficient in converting supercooled liquid water to snowfall while small storms tend to be inefficient and therefore, are more susceptible to cloud seeding. To test this conceptual picture, supercooled liquid water flux and precipitation amounts were compared for 4 different mountain regions in Arizona, Colorado and Utah. Supercooled liquid water flux totals were estimated for entire storm periods from vertically-integrated microwave radiometer measurements and wind speeds within about 1 km of the mountain crest, corresponding to the layer expected to contain most of the supercooled liquid water. Per storm precipitation totals were measured near the radiometer sites.

Comparison of storm total supercooled liquid water flux with total precipitation revealed apparent significant relationships between the two variables at all sites. The larger supercooled liquid water flux-producing storms tended to have larger precipitation amounts. When the effect of storm duration was removed, partial correlations coefficients between supercooled liquid water flux and precipitation were significant at 3 of the mountain sites. None of the data sets supported the concept that large precipitation-producing storms are highly efficient in converting supercooled liquid water flux to snowfall. This suggests that large storms are efficient during some phases when abundant snowfall is produced, but inefficient during other phases when supercooled liquid water flux is abundant. This hypothesis was tested for one well-observed storm. Precipitation efficiency was estimated throughout the storm's duration by comparing snowfall with upwind supercooled liquid water flux plus ice flux. The prefrontal phase was very inefficient and produced most of the total supercooled liquid water flux. The frontal phase was more efficient and about half the flux of liquid and ice was converted to snowfall. The postfrontal phase had little supercooled liquid water flux but significant ice flux. However, it was inefficient in converting cloud ice to snow on the ground.

One to a few storms at each site produced most of the seasonal total supercooled liquid water flux. From 50 to 67 pct of all storms at each site produced small amounts of supercooled liquid.

SUMMARY AND CONCLUSIONS

Storm total SLW flux estimates and precipitation measurements were examined with data sets from 4 mountain regions: the Mogollon Rim of Arizona; the Grand Mesa of Colorado; and the Tushar Mountains and the Wasatch Plateau of Utah. Periods with microwave radiometer observations of SLW were limited to 2 mo on the Mogollon Rim and Wasatch Plateau, and to 5 mo at the two other sites.

An apparently significant relationship (rank correlation coefficient) existed between larger flux-producing storms also having greater precipitation amounts. When the effect of storm duration was removed, the partial correlation coefficient between flux and precipitation was still significant at 3 of the 4 mountain regions. Significant partial correlations existed between precipitation and storm duration (controlling for flux) at all locations.

None of the four data sets support the concept that large precipitation-producing storms are highly efficient in converting SLW flux to snowfall. The reverse was indicated; that is, storms with larger precipitation totals tended to have greater SLW flux. This indication suggests that large SLW flux-producing storms may be efficient in snowfall production during some phases and inefficient during other phases.

One example from a moderate-sized Utah storms supported this conceptual picture. A comparison of precipitation flux to SLW and ice flux was used as a means of computing precipitation efficiency. The prefrontal stage of this storm was very inefficient and contributed most to the total SLW flux. The frontal stage had a higher SLW production rate, but was more efficient and of shorter duration, and thus contributed less to the total SLW flux. The post frontal stage contributed the least to the total SLW flux. It was also found that the final postfrontal stage was only about 60 pct efficient even though almost no SLW existed. Much of the radar-estimated cloud ice apparently did not fall to the ground as precipitation.

The frequency of small SLW-producing storms (<50 Mg flux per meter) was similar at all four locations, ranging from 50 to 67 pct of all storms. The frequency of large storms, with greater than 400 Mg m^{-1} ranged from 0 to 9 pct. Both the Wasatch Plateau and the Grand Mesa had a single exceptionally large SLW-producing storm exceeding 100 Mg m^{-1} . In each area one to a few storms produced most of each season's SLW flux.

The storm frequency was markedly higher for the Grand Mesa, averaging 13 storms per month compared with 8 storms per month over the Wasatch Plateau, 5.5 per month over the Mogollon Rim and 5.4 per month over the Tushar Mountains. However, total observational periods for these mountain areas were limited. While a higher frequency of storm passages would be expected at more northern latitudes (i.e., the Wasatch Plateau and the Grand Mesa), a longer sampling period would be needed to determine if significant differences really exist in SLW episode frequency.

Distributions of storm durations are similar in Tables 1.2 and 3, with from 50 to 70 pct of all storms lasting less than 24 hours. Only 3 of 11 (27 percent) of the Mogollon Rim storms listed in Table 4 were that brief.

Because seeding potential can be expected to be related to SLW flux (among other factors), the major SLW-producing storms obviously should be identified for treatment. Identification can be done with real-

time observations of SLW, using icing rate meters and radiometers. Rapid response seeding can be done with remote-controlled generators.

The previous discussion concerning total SLW flux per storm episode may give the impression that the only periods worth seeding have large amounts of vertically integrated SLW. In fact, Super and Boe (1988) examined the 2 mo of hourly (not storm total) microwave radiometer data from the Mogollon Rim to show that 44 pct of the total flux for the season was due to the 81 pct of all hours with mean cloud liquid water amounts of only 0.15 mm or less. Their study also showed that the 5 pct of all hours with liquid amounts in excess of 0.35 mm yielded almost 30 pct of the total flux. Similar results were shown for the Grand Mesa (Boe and Super 1986). These studies suggest that seeding may be appropriate both when SLW is abundant and when it is limited. Hours with large SLW amounts produce significant flux but are relatively rare. The numerous hours with small SLW amounts also produce significant flux over an entire winter.

8.9. Super, A. B., and J. T. McPartland, 1993: Preliminary estimates of increased runoff from additional high elevation snowfall in the Upper Colorado River Basin. *J. Weather Modification*, 25, 74-81.

ABSTRACT

Evaluations of winter orographic cloud seeding projects often have been based on precipitation because of difficulties associated with evaluation by stream flow at many locations. But most sponsors are primarily interested in the amount of additional streamflow that might be expected from successful cloud seeding. Preliminary estimates have been made of the percentage increases in streamflow that might result from increased snow water equivalent in the Upper Colorado River Basin. This was done by fitting linear regression equations to paired streamflow and snow water equivalent observations from several mountain watersheds for which streamflow was not significantly affected by transbasin diversions or upstream regulation of flows. The regression equations were used to predict percentage seasonal and annual streamflow enhancements for a 10 pct increase in mean April 1 snow water equivalent.

Predicted seasonal streamflow increases ranged from 6 to 21 pct, with most drainages estimated to have 10 pct or more additional runoff. Possible reasons for differences in predicted streamflow are discussed. The reasons include snow water equivalent measurements that are unrepresentative of the watersheds, variations in geology and vegetation, and drainage slope and aspect which affect incoming solar radiation. It is suggested that as cloud seeding technology improves, more attention should be given to targeting areas that maximize streamflow enhancement.

SUMMARY

This study estimated the percentage increases in runoff that might be expected from 10 pct snowpack increases in unregulated mountain watersheds in the Upper Colorado River Basin. April 1 SWE data collected by the SCS were used together with GS stream gauge observations to develop snowpack-runoff relationships for 16 individual drainages. Observations from two small experimental watersheds were also used to develop linear regression equations between streamflow and near-maximum SWE. These relationships were used to estimate the percentage increase in runoff predicted for a 10 pct increase in snow accumulation during a mean season.

This approach suggested that April through July total runoff would increase at least 10 pct in most watersheds for a 10 pct increase in the mean snowpack. However, some basins indicated increased on only 6-8 pct. Closer examination suggested that snow courses in or near some watersheds, though well correlated with runoff, poorly represented actual snowpack conditions throughout the watershed. These snow courses tended to be low elevation courses for which the calculated linear regression equations predicted substantial flow even with zero SWE on April 1. In general, the higher the snow course elevation, the greater was the prediction of percentage increase in runoff.

About 20 pct runoff enhancements were predicted for 2 of the basins in Table 2 and for 1 small experimental watershed with representative SWE observations and limited slope. Two of these 3 basins are known to have relatively impervious base material. Only 8 pct runoff enhancement was predicted for a second small experimental watershed with very permeable base material. It seems probable that subsurface flow reduced the measured runoff in that drainage.

Other important factors believed to influence the snowpack-runoff relationships are those that cause variability in sublimation and evapotranspiration losses (slope, aspect, vegetation). All five drainages listed in Tables 1 and 2 with predicted runoff increases less than 10 pct had steep south-facing or southwest-facing slopes which would maximize such losses. The geology of at least two of these drainages could reduce runoff.

A given percentage snowpack increase at higher elevations probably will result in a larger runoff increment than the same percentage increase in the lower elevation snowpack of the basin. The evidence in this paper supports that concept, and higher elevations usually have greater SWE, which suggests that a cloud seeding projects should emphasize targeting of the higher elevations in mountain watersheds. However, slopes exposed to strong solar radiation and/or sustained winds may lose much of their windfall. As the technology of winter weather modification improves, more attention should be given to targeting areas which maximize runoff.

The conversion of snowpack to runoff is a complex, nonlinear process. Observations from well-instrumented watersheds, coupled with physically-based numerical models, could be used to provide accurate and reliable estimates of runoff responses to enhanced snowpack. In the meantime, the estimates made by this simpler approach are probably reasonable, conservative first approximations. These estimates indicated that in most mountain locations in the Upper Colorado River Basin, a 10 pct increase in SWE should result in at least a 10 pct increase in spring and summer runoff. Runoff increases up to 20 pct may be expected from some drainages. Conversely, drainages with high evapotranspiration losses or very permeable soils may produce less than 10 pct runoff increases.

1994 articles and papers:

10. Heimbach, J. A., Jr., and W. D. Hall, 1994: *Applications of the Clark model to winter storms over the Wasatch Plateau. J. Weather Modification*, 26, 1-11.

ABSTRACT

The configuration of the Clark mesoscale model to a field experiment conducted over the central Utah Wasatch Plateau experimental area is briefly described. Its application is demonstrated using one case from the early winter 1991 Utah/NOAA Cooperative Atmospheric Modification Research Program. Observations of sulfur hexafluoride and ice nuclei were used to test the model. The results were in

reasonable agreement with field measurements of plume positions; however, plume concentrations were unpredicted. The model was run with a Kessler warm rain parameterization to examine the characteristics of liquid condensate. Patterns of liquid water predicted by the model suggest that depletion of liquid water to the lee of the crest could be due to subsidence warming. This complicates the estimation of liquid water depletion through precipitation processes.

DISCUSSION

The model results were in reasonable agreement with observations of plume positioning. The observed meandering of plumes, transport over lower terrain and shallow vertical dispersion were predicted by the model. The model's elevated concentrations were smaller than those inferred by SF₆ observations. This is likely for three reasons: 1) the tracer was given an instantaneous dispersal throughout one grid bin upon release; 2) the model predicted less vertical transport than reality; and 3) comparisons were done using peak SF₆ observations; however, the use of average SF₆ concentrations, though somewhat ambiguous, could not explain all the difference.

The model illustrated several points which should be considered in planning future winter orographic weather modification operations which employ surface sources.

- Seeding material can be confined to a depth of several hundred meters over the terrain.
- The horizontal and vertical positions of the release point are critical. In this study the best release points were on the windward slopes of the barrier to take advantage of terrain-forced vertical motions.
- Pooling of seeding material can occur in the valley areas, and its transport can be guided by the character of lower terrain.

The most critical factor in ground-based targeting is placing the source in an area having positive vertical velocity near the surface. Typically, this is windward of the crest. Areas at the crest or just downwind showed small or negative vertical velocities in simulations. Valley sites can be poor locations because the vertical motion fields may not reach low enough and the valley surface winds are too poorly organized to provide consistent transport.

The use of an upwind seeding site, e.g., the San Pitch Mountains, was modeled (not illustrated in this paper) and found to have some possibility of success. An upwind release site has the advantages of providing a broader plume, earlier nucleation and opportunity for greater vertical transport. The drawbacks include targeting inconsistencies, increased lead time and dilution. It would be worthwhile to try one or more test releases from the San Pitch Mountains using a mobile source of AgI. SF₆ is not the tracer of choice for this because of the large dilutions anticipated while crossing the Sanpete Valley.

It would be useful to model transport and diffusion using a Lagrangian transport scheme. The Lagrangian treatment uses a coordinate system which follows effluent particles rather than remaining stationary. This eliminates the effect of the initial dispersion of tracer material and would give a better visual display of plume characteristics. A finer innermost mesh is needed to better simulate the effects of flow around the terrain of the experimental area. In particular, the canyons, which are important in the transport of low elevation seeding material, are not well-represented in the model. Finally, the model is being implemented on workstation environments. Though not possible to run the model with a fine resolution

on a workstation, it does offer the ability to utilize the model in a field environment, enabling an operational application in a field environment.

8.11. Super, Arlin B., 1994: *Implications of early 1991 observations of supercooled liquid water, precipitation and silver iodide on Utah's Wasatch Plateau. J. Weather Modification*, 26, 19-32.

ABSTRACT

The Utah/NOAA Atmospheric Modification Program conducted an observational program in early 1991, with additional support from the Bureau of Reclamation. A summary is presented of observations obtained on the Wasatch Plateau of central Utah which includes SLW (supercooled liquid water), precipitation, AgI (silver iodide) IN (ice nuclei), air and dewpoint temperature, and wind velocity. With the exception of AgI ice nuclei, measurements were made on 20 days with storm conditions. Silver iodide was monitored during part or all of a subset of 12 days when valley AgI generators were being operated.

It is shown that abundant SLW existed during many hours, and a large fraction of these hours did not have precipitation observed on top of the Plateau. The SLW flux over the Plateau-top's windward edge exceeded the average precipitation on top of the Plateau. These findings suggest significant seeding potential may exist.

Acoustical ice nucleus counter observations were adjusted to temperatures typical of AgI plume tops. Aircraft measurements showed the plume tops were usually less than 1 km above the Plateau. The adjusted ice nucleus observations suggest effective AgI ice nuclei concentrations were too low for productive seeding much of the time when SLW was present. The main problem appears to be the warm temperatures of the SLW during most storm periods. Effective concentrations of AgI ice nuclei are not expected at such temperatures with the generators and release rates used in the Utah operational seeding program. However, these estimates were based on a 1981 generator calibration in a cloud simulation laboratory which may not be totally representative of winter orographic clouds. Direct observations are needed of ice particle concentrations caused by seeding orographic clouds for the range of conditions typical of winter storms.

The challenge is to develop means of routinely targeting the SLW zone with adequate concentrations of seeding-caused ice crystals which can start the precipitation formation processes in naturally inefficient clouds. A number of approaches are suggested which could make the Utah operational seeding program more effective.

CONCLUSIONS AND RECOMMENDATIONS

The 1991 data set is encouraging in that many hours had abundant SLW over the west edge of the Plateau top. A large fraction of the wetter hours had no detectable precipitation, suggesting significant seeding potential may exist if ice crystals can be produced in the SLW cloud. The average SLW amount during the wetter hours with precipitation was even higher than during the wetter hours with no precipitation, again suggesting seeding potential.

Huggins et al. (1992) presented estimates of SLW flux per storm episode for the 1991 field season. For the 20 days discussed here, the estimates of total SLW flux exceeded 2100 Mg per meter of crest line. If that amount of water was converted to precipitation of uniform intensity over the width of the Plateau

(about 10 km) the average precipitation would be 8.3 in., almost twice the observed amount. This calculation suggests that a substantial amount of excess SLW was transported over the Plateau as has been found over other mountain barriers in the intermountain West (e.g., Super and Huggins 1993). The portion of excess SLW that cloud seeding can convert to precipitation has yet to be demonstrated. However, the "raw material" needed for seeding to be effective certainly exists in relative abundance. The availability of abundant SLW has been assumed for decades but has been verified only in the past several years.

The 1991 data set also raises questions about the effectiveness of the Utah operational seeding program. Physical reasoning was presented that suggested seeding rates may be too low, at least for warmer storms. Admittedly, the estimates of effective IN may be flawed by instrumentation limitations and possible unrepresentativeness of CSU generator calibrations for winter orographic clouds. However, in the absence of better information, the observations and calculations presented in this paper indicated there is reason to be concerned. Production of adequate concentrations of seeded ice particles is basic to successful seeding. This topic deserves further investigation in the Utah operational program in particular, and in seeding programs in general.

The main problem for the Utah operational seeding program appears to be the relatively warm SLW temperatures combined with the strong temperature dependence of AgI as an effective IN. This problem could be partially remedied by increasing the source strength of potential IN using improved seeding generators and solutions and higher AgI output rates. However, the SLW is probably too warm for effective seeding with any practical AgI solution and seeding rate some of the time. Even transporting the AgI to higher, colder altitudes by aircraft seeding would frequently be ineffective because the AgI would then be above the SLW needed to nucleate ice crystals.

This is not to suggest that more effective AgI solutions and higher output generators should not be employed. Anything done to increase the output of effective IN should help seeding effectiveness. However, practical limits exist regarding what can be done with AgI. A large fraction of the winter storms, tending to be those with highest SLW amounts, likely cannot be effectively seeded with present AgI solutions because the SLW is simply too warm.

The problem of seeding warm SLW with AgI is not unique to Utah. The statistical analysis of Super and Heimbach (1983) strongly suggested that the warmer, wetter half of Montana winter orographic storms did not respond to AgI seeding, but the colder, drier storms ($< -9^{\circ}\text{C}$ at 2600 m) clouds did respond. The State of California has been developing a propane seeding technology because the warm SLW problem is severe there (Reynolds, 1991). Propane seeding can create high concentrations of ice crystals at temperatures colder than 0°C . Remote-controlled propane dispensers are much more economical than remote-controlled AgI generators, and are more reliable because they are much simpler devices. However, they must be located in or very near clouds to be effective.

It is recommended that the State of Utah pursue a number of approaches aimed at increasing the effectiveness of the operational seeding program. High output generators and more effective AgI solutions should be considered. Higher altitude release sites would increase the frequency of targeting SLW clouds. The possibility of high altitude releases from mountains upwind from the target areas deserves further exploration. Ongoing analysis suggests that AgI releases above canyon mouths may be more effective than AgI releases from valley floor locations. Finally, propane seeding should receive serious attention because even warm storms can be seeded as long as the propane dispensers are located at high altitudes within the orographic cloud.

The 1991 field program measurements have confirmed for the Wasatch Plateau of central Utah some of the earlier findings from the Tushar Mountains of southern Utah. Namely, abundant SLW is available during phases of many winter orographic storms which should provide frequent seedable opportunities. Most of the SLW is within 1 km of the mountain crests at relatively high temperatures. The challenge is to develop the means to routinely target the SLW zone with adequate concentrations of artificially nucleated ice crystals which can start the precipitation formation processes in naturally inefficient clouds.

8.12. Super, A. B., and E. W. Holroyd, 1994: Estimation of effective AgI ice nuclei by two methods compared with measured ice particle concentrations in seeded orographic cloud. *J. Weather Modification*, 26, 33-40.

ABSTRACT

The Utah/NOAA Atmospheric Modification Program conducted a field program during early 1991, with additional support from the Bureau of Reclamation. Several aircraft missions were flown over central Utah's Wasatch Plateau to monitor plumes of AgI (silver iodide) and tracer gas, and microphysical changes caused by the AgI seeding. This paper discusses one mission during which high-altitude, ground-based AgI release resulted in obvious enhancements in ice particle concentration. Fast-response observations of co-released tracer gas, presumably collocated with the AgI plumes, were used to define seeded zones and crosswind control zones.

Two methods were used to estimate concentrations of AgI ice nuclei effective at cloud temperatures sampled by the aircraft. One method used tracer gas concentration measurements while the other was based on acoustical ice nucleus counter observations. Both methods were partially based on a cloud simulation laboratory calibration of the AgI generator done over two decades ago. The methods were compared with the ice particle concentrations apparently caused by the AgI seeding. Both approaches were found to provide a reasonable first approximation for the particular AgI aerosol produced and the sampled cloud conditions. However, caution should be exercised in applying the estimation approaches to other cloud conditions and AgI aerosols.

SUMMARY AND CONCLUSIONS

A specially-instrumented aircraft was used to monitor AgI and SF₆ plumes co-released from a high-altitude site on the Wasatch Plateau of central Utah during early 1991. An NCAR IN counter measured AgI while a fast-response detector measured the SF₆ tracer gas. A 2D-C particle imaging probe monitored the IPC within and crosswind of the AgI/SF₆ plumes. Other sensors observed cloud temperature, liquid water content, aircraft position and other variables.

Obvious increase in IPC were associated with the SF₆ plume on the 17 February aircraft mission. Observations from this mission were used to estimate concentrations of AgI IN effective at the sampling temperatures. These estimates were compared with measurements of the IPC enhancement with the SF₆ (and presumably collocated AgI) plume. The IPC enhancement was considered to be the difference between in-plume IPCs and the natural IPCs in crosswind control zones.

Two methods were used to estimate effective AgI IN concentrations. One method was based on SF₆ gas concentration measurements and the other on NCAR IN observations. Both methods relied on cloud simulation laboratory calibrations to establish the source strength and temperature dependence of

generated AgI IN. The representativeness of these calibrations for winter orographic clouds is open to question. Nevertheless, in the absence of IPC measurements, cloud simulation AgI generator calibrations have been used in designing several seeding experiments and operational programs.

The ratios of AgI IN estimates by the two methods indicated that the more quantitative SF₆ observations provided on average, about 4-5 times higher values than the NCAR IN counter measurements. The differences of AgI IN estimates may be partially due to AgI losses by nucleation and scavenging and partially to instrumentation limitations. Cloud characteristics and residence times are quite different between winter orographic clouds and NCAR IN counter (and CSU) cloud chambers. The NCAR IN counter uses a dense cloud in an attempt to compensate for the short residence time of IN.

The SF₆ gas measurement method provided first-approximation estimates of measured IPCs with all but one of the estimates within a factor of six. Most estimates were higher than observed IPCs. First-approximation estimates were also provided by the NCAR IN counter method, although values were lower than provided by the SF₆-based method.

The single experiment reported suggests that seeding-caused IPCs can be estimated by tracer gas or NCAR IN counter observations to within about one order of magnitude for the particular AgI generator and aerosol used, and the sampled cloud conditions. While this result is encouraging, further observations would be needed to test whether similar results can be obtained with other AgI generators, AgI solutions and cloud conditions. In view of differences between orographic and simulated clouds, and of known instrumentation limitations, the apparent good agreement from the single experiment may be somewhat fortuitous.

Because of the uncertainties involved in AgI IN estimation, and in ice nucleation processes, it is clearly preferred to directly measure seeding-caused IPCs within winter orographic clouds. More direct IPC measurements must be made if the field of winter orographic cloud seeding is to advance in scientific understanding and credibility. However, such observations are difficult and expensive to obtain, and may be impractical for many programs. Further testing of indirect methods may provide an alternative approach to direct observation of IPCs. It is recommended that any further tests of indirect methods use a current AgI generator calibration from the CSU or similar facility. Use of an improved IN counter, based on current technology, would also be very desirable.

1995 articles and papers:

8.13. DeMott, P. J., A. B. Super, G. Langer, D. C. Rogers, and J. T. McPartland, 1995: Comparative characterizations of the ice nucleus ability of AgI aerosols by three methods. *J. Weather Modification*, 27, 1-16.

ABSTRACT

Three methods were used to assess the ice nucleating ability of different AgI-based aerosols produced using two solution combustion generators. The standard method employed was an isothermal cloud chamber which has been historically used for "calibrations" of ice nucleus aerosol generators. Comparisons with historical data showed consistency over a 20 year period for one generator, but not for another. Data on rates of ice crystal formation were used to infer operative ice formation mechanisms, and make inferences to the relative utility of the different aerosols in the atmosphere. Comparative measurements of ice nucleus effectiveness at -20 °C were made using two NCAR counters that have been

used operationally to trace the aerosols tested. Results showed that these devices can give self-consistent results and typically measure about 33% of the ice nuclei measured in the larger cloud chamber and 25% of the total AgI aerosols present. These results varied depending on the ice nucleus aerosol tested, presumably due to differences in particle size and chemistry. Measurements of the ice-forming ability of one aerosol ($\text{AgCl}_{0.22}\text{I}_{0.78}\cdot 0.125\text{NaCl}$) were also made with a continuous flow ice-thermal diffusion chamber. These measurements showed that the water supersaturation dependence of the ice formation rate by condensation-freezing for these aerosols varies by more than three orders of magnitude between 0 and 7% supersaturation. Ice formation was nearly instantaneous above 7% supersaturation for all aerosols capable of acting as ice nuclei. The various measurements taken will permit the quantitative transfer of laboratory results on ice nucleus ability to a range of expected atmospheric conditions.

SUMMARY AND CONCLUSIONS

Yield values in the CSU isothermal cloud chamber were obtained for aerosols produced from combusting 2 and 3 weight % AgI solutions using the MSU Skyfire generator. The yields for aerosols from the 2% AgI solutions were not substantially different than for 3% AgI solutions, indicating that no added benefit exists for using 3% AgI solutions in warmer supercooled cloud conditions. Comparison of 3% AgI solution aerosols in the current tests with those tested in the MSU generator in 1972 gave excellent agreement. Ventilation of the generator at higher wind speeds increased the generator yield across the temperature spectrum tested by a factor of 2 to 10 times. This is an unusual result for most generators at the warmest temperatures since the typical effect of ventilation is more rapid quenching of the burn and production of smaller particle sizes which usually are less efficient at warmer temperatures. This may merit further investigation.

Yield values obtained using the NAWC generator indicated greatly enhanced ice formation activity warmer than -10°C for AgI- NH_4I -acetone water solutions (2% AgI) compared to earlier tests in 1978 and 1981. Apparently, some changes to generator combustion design have been made. As a consequence, a chemical change to a solution to produce very efficient $\text{AgI}_{0.78}\text{Cl}_{0.22}\cdot 0.125\text{NaCl}$ composite nuclei, produced only a slight enhancement in yield at the warmest temperature tested (-6°C). Nevertheless, these aerosols do appear to offer the potential for enhanced yield at even warmer temperatures. This would have to be verified by further testing. Ventilation of the NAWC generator at higher wind speeds was found to increase yield by about 10 times at -20°C , but decrease the yield by 10 times at -6°C . This was consistent with results obtained in previous calibrations and is believed to reflect the dependence of activation on particle size (smaller during ventilation).

Examination of the ice formation rates in the isothermal cloud chamber indicated that the 2% AgI aerosols produced by both the MSU and NAWC generators functioned by contact-freezing at temperatures warmer than -16°C in the ICC. Previous tests of the 3% AgI MSU generator aerosols for higher LWC and higher droplet concentrations in the ICC indicated faster ice formation rates in proportion to droplet concentration, quantitatively supporting this conclusion. Ice formation rates were faster at temperatures below -16°C . The ice formation mechanisms in this temperature regime could not be discerned.

Use of the solution containing ammonium iodide and paradichlorobenzene in the NAWC generator did not force a rapid condensation-freezing nucleation process at water saturation in the ICC. Nevertheless, evidence does indicate that a slower condensation-freezing process did occur. This ice formation process could provide substantial advantages in natural clouds over aerosols which realize their greatest activity as contact-freezing nuclei. This is because the ice formation rates by contact-freezing are dependent on the droplet concentration at water saturation, while the ice formation rates by condensation-freezing are not. Consider, for example, a natural orographic cloud with 100 droplets cm^{-3} of similar sizes to those in the

ICC tests. In this case, the contact-freezing rate constants expected in the natural cloud for MSU and NAWC natural draft AgI aerosols are obtained by multiplying the k_{act} values in Table 3 ($\sim 0.08 \text{ min}^{-1}$ at $T \geq -16^{\circ}\text{C}$) by the ratio of in the ICC versus natural droplet concentrations ($100 \text{ cm}^{-3}/2100 \text{ cm}^{-3}$). For a 20 minute transit time at a constant temperature through the natural cloud, this implies that only about 7% of the potential yield (Tables 1 and 2) would be realized. For NAWC AgI- $\text{Cl}_{0.125}\text{NaCl}$ aerosols, the rate would be 0.1 min^{-1} regardless of droplet concentrations. Thus, in 20 minutes transit at one temperature, 86% of the potential yield (Table 2) would occur. An order of magnitude difference in ice crystal formation is inferred to be possible by switching aerosols from AgI to AgI- $\text{Cl}_{0.125}\text{NaCl}$. Future studies of these and other aerosols tested for this paper would benefit from analysis of dependence of ice formation rate on varied cloud droplet concentrations and humidities, in order to validate mechanisms.

The measurements made with two NCAR counters coordinated to sample the same aerosols used in ICC tests indicated that the NCAR counters sampled ice nucleus aerosols at about one-third of the efficiency of the ICC at -20°C after dilution airflow corrections are applied to the ICC data. In comparison to raw ICC results, such as are commonly reported from the CSU laboratory, the NCAR counters detected closer to two-thirds of the ice nuclei. There appeared to be differences in this counting efficiency factor as a function of the aerosol tested, but not enough data were collected to confirm this. Nevertheless, the counting efficiency noted is a factor of about ten higher than measured for two other NCAR counters sampling different AgI aerosols by Sackiw et al. (1984). This could be related to differences in the counter response to the different aerosols tested in the two studies. Although the ice formation mechanism operating within the NCAR counters is unknown for the aerosols tested, the amount of ice crystals formed compared to the ICC are reasonable if one assumes that a contact-freezing process dominated, but was limited by the shorter residence time within the counters compared to the cloud chamber.

The results of the ICC/NCAR counter cross-calibration should be extremely useful for quantifying the NCAR data in field experiment studies of cloud seeding using the aerosols tested. The excellent consistency notes between the two units tested was another positive result in this regard. We recommend cross-calibrations of the type performed here for NCAR counters before use in field operations.

The CFD experiments on AgI- $\text{Cl}_{0.125}\text{NaCl}$ aerosols from the NAWC generator yielded several interesting results which demonstrate the utility of this technique alone or in concert with other measurements of ice nuclei. The results, which by their nature did not permit contact-freezing nucleation to be observed to any degree, indicated that these aerosols required greater than 4% water supersaturation to achieve 10% instantaneous activation by condensation-freezing at -16°C . These conditions are probably met on some occasions during field generation due to the moisture released during combustion (Finnegan and Pitter, 1988). Combined with the ICC results, the CFD results also give vital information permitting calculations of ice formation rates in real clouds. This will be the subject of future analyses and experimentation. The CFD results also show that it will be readily possible to easily and quantitatively describe differences in chemically different (e.g., more hygroscopic or more hydrophobic) ice nuclei in future experiments.

Concerning the practical matter of using such an instrument simply for tracking the transport of manmade ice nuclei by aircraft, the results simply that the device should be operated at a high supersaturation to facilitate efficient detection.

8.14. Holroyd, E. W., J. A. Heimbach and A. B. Super, 1995: Observations and model simulation of AgI seeding within a winter storm over Utah's Wasatch Plateau. *J. Weather Modification*, 27, 36-56.

ABSTRACT

Observations from a cloud seeding experiment conducted over the Wasatch Plateau of central Utah were analyzed for treatment effect and were modeled. The day was characterized by weak surface winds, light snowfall and weak convection embedded in a thin orographic cloud during the final stages of a storm. Silver iodide was released from a generator well up the windward (west) slope of the Plateau. Seeded periods and locations were defined using measurements of co-released SF_6 tracer gas and a drifting frame of reference. Seeded and nonseeded periods and domains were defined using the derived plume history. A strong seeding signal was found in the occurrence of ice particles, both on the Plateau top and at aircraft levels. Calculations based on van-mounted 2D-C probe observations along the Plateau top's west edge indicated increased snowfall rates in the silver iodide plume, primarily due to aggregates. While some precipitation gauge observations farther downwind suggested possible increased snowfall, the evidence was not definitive and any seeding-caused snowfall was quite limited in amount. Applications of the Clark mesoscale numerical model suggested the case was characterized by weak and shallow clouds principally driven by orographic influences with little buoyant contribution. The simulated tracer and cloud patterns were associated with orographic lifting and gravity waves. The model correctly predicted plume transport from the release point over the target area, but at a slower rate than indicated by field measurements. The plume core was predicted to be transported over the Radar-Radiometer site and somewhat south of the Target site to a height of about 1 km above the Plateau in good agreement with observations.

SUMMARY AND CONCLUSIONS

The 21 February 1994 case was analyzed for plume characteristics including seeding responses for a single AgI plume co-released with SF_6 tracer gas well up the windward side of the Wasatch Plateau. The day was characterized by weak winds primarily from the southwest with weak convection enabling vertical transport of AgI to flight levels. The exposure of sites and mobile sampling platforms to the plume was estimated using a frame of reference which moved with the average wind. This enabled spatial and temporal coordination of multiple plume encounters, and allowed a uniform objective definition of nonseeded periods and locations. For the sampling aircraft, nonseeded portions of a flight path were 24 s flight intervals 12 s on either side of the co-released SF_6 plume. The nonseeded zones for the instrumented van were 2 km distances 1 km outside the SF_6 plume.

The plume was estimated to have been over particular ground sites for 4.25 h and to have generally moved from 235 degrees with a short period having a more southerly component. The angular plume width over the west flight track was estimated to have been 15 degrees with a brief wider period associated with a wind shift. Vertical plume transport to the Plateau top and to flight levels was rapid in the presence of limited horizontal winds speeds.

High concentrations of ice particles were associated with measured and predicted plumes at locations sampled by the van and aircraft. Ice particle concentrations and precipitation rates were enhanced, compared to nonseeded zones, by factors of about 10 for upwind highway van measurements, 40 for west track aircraft measurements, and variable amounts for east track aircraft passes. Ice water contents were always greater in the plume than in the nonseeded zones. Particle trajectories and concentration patterns indicated that most growth and precipitation occurred near the west track, where there was the most SLW

available. Aggregation of high concentrations of ice particles appeared to be the mechanism for greater precipitation rates in the plume. Little snow was left to fall over the eastern ridge of the Plateau. Winds were typically light during this experiment so that seeded snowfall for windier cases might be expected to settle further eastward.

Comparisons of precipitation totals between seeded and nonseeded gauges were suggestive that seeding may have produced a limited snowfall increase over the period of the experiment of perhaps 0.5 mm at some gauges. However, one eastern seeded gauge received less snowfall than two nonseeded gauges also on top of the Plateau. Analyses of observations and physical reasoning suggest that most seeded snowfall settled to the Plateau top before crossing to its east edge, and perhaps before reaching the middle of the Plateau top at gauge TARSW. In retrospect, one or more gauges would have been useful along the upwind highway a few km north of RRS.

Updrafts predicted by the Clark model were associated with the windward edge of the Plateau and were generally limited to 0.5 m s^{-1} near the surface. There were areas of stronger down drafts over the Plateau, reaching speeds of -1.5 m s^{-1} . The complex gravity wave pattern forced a secondary maximum of tracer material several km south of TAR and some additional condensation over the northern portions of the eastern flight track.

The model suggests the case had weaker transport and diffusion of tracer material over the Plateau than indicated by field measurements. The plume transport time over the Plateau was slower than reality; however, the model ultimately simulated transport of AgI into liquid water cloud over the Plateau. The heights to which the simulated plumes were transported were in reasonable agreement with aircraft observations, but the simulated lateral spread was excessive at the surface. The model's smoothed terrain likely contributed to the less organized transport because the simulated canyons were shallow enough to limit the funneling of the poorly organized surface winds. The actual terrain consisted of a pronounced canyon downwind of AHS which likely limited crosswind horizontal dispersion within the canyon. The simulated clouds and ice were weak and shallow because buoyancy was not part of their formation. It is believed that buoyancy from solar heating did contribute to the observed clouds, and for that reason also contributed to a more vigorous vertical plume transport than was simulated. Overall, the model simulation produced a reasonable first-approximation of reality.

In summary, AgI seeding during this experiment produced strong microphysical evidence of markedly enhanced ice particle concentrations on the Plateau top and at aircraft levels. Plumes released on the windward slope were readily transported over the Plateau in spite of limited horizontal winds. Plume widths were limited, suggesting seeding generators at similar high altitude sites should be spaced no more than 5 km crosswind. Horizontal dispersion from other high altitude sites could be more or less than from AHS depending upon local topography.

Seeding apparently increased the snowfall, especially on the western portion of the Plateau top, but accumulations were limited. Seeding appeared to significantly increase the aggregation of snowflakes along the upwind highway. Best estimates of snowfall rates caused by seeding are 0.4 mm h^{-1} based on 2D-C estimates along the upwind highway (Table 2) and less than half that rate from gauges on the central and eastern portions of the Plateau top (Sec. 6) Of course, SLW amounts were quite limited during this week and diminishing final portion of the storm, so seeding potential would be expected to be quite limited as well.

Overall, the results of this experimentation are in general agreement with the current physical understanding of how winter orographic seeding should work.

8.15. Huggins, A. W., 1995: *Mobile microwave radiometer observations: spatial characteristics of supercooled cloud water and cloud seeding implications*. *J. Applied Meteorology*, 34, 432-446.

ABSTRACT

Previous studies of the spatial distribution of supercooled liquid water in winter storms over mountainous terrain were performed primarily with instrumented aircraft and to a lesser extent with scans from a stationary microwave radiometer. The present work describes a new technique of mobile radiometer operation that was successfully used during numerous winter storms that occurred over the Wasatch Plateau of Central Utah to determine the integrated depth of cloud liquid water relative to horizontal position on the mountain barrier. The technique had the advantage of being able to measure total liquid from the terrain upward, without the usual terrain avoidance problems that research aircraft face in cloudy conditions. The radiometer also collected data during several storms in which a research aircraft could not be operated because of severe turbulence and icing conditions.

Repeated radiometer transects of specific regions of the plateau showed significant variability in liquid water depth over 30-60 min time periods, but also revealed that the profile of orographically generated cloud liquid was consistent, regardless of the absolute quantities. Radiometer liquid depth generally increased across the windward slope of the plateau to a peak near the western edge of the plateau top and then decreased across the relatively flat top of the plateau. These observations were consistent with regions where maximum and minimum vertical velocities were expected, and with depletion of cloud liquid by accretional ice particle growth across the mountain barrier. A comparison of data from the mobile radiometer and a stationary radiometer verified the general decrease in liquid depth from the windward slope to the top of the plateau and also showed that many liquid water regions were transient mesoscale features that moved across the plateau.

Implications of the results, relative to the seeding of orographic clouds, were that seeding aerosols released from valley-based generators could at times be inhibited by stable conditions from reaching appropriate supercooled liquid water regions and, as found, by others, the region of cloud most likely to be encountered by an AgI seeding agent released from the ground was also relatively warm compared to the ice-forming capability of the particular agent used in these experiments. Also, one convective case study that exhibited relatively warm temperatures in the cloud layer indicated that even in conditions that permit vertical transport to supercooled liquid zones, sufficient time for ice particle growth and fallout from seeded plumes on this plateau may be lacking.

CONCLUSIONS

A mobile microwave radiometer system has been developed that has proven to be very useful in the study of orographic liquid cloud development. The system was operated during numerous winter storms on all weather roads that cross the Wasatch Plateau of central Utah. In addition to the measurement of microwave emission by liquid water and water vapor, the measurement of outside air temperature permitted the detection of temperature inversions in the mountain-valley system. Location measurements were made using geographic landmarks and road markers, but the system has now been equipped with a global positioning system (GPS) so atmospheric data and location data can be merged into the same dataset.

Provided an adequate road network is available, the mobile radiometer can collect data in all but the most adverse conditions. Several experiments on the plateau were conducted by the mobile radiometer when

aircraft flights were suspended due to severe turbulence and icing. The system therefore allows measurements to be taken in a wider variety of storm situations, including those where cloud liquid is primarily confined to regions below the minimum altitude allowed for aircraft terrain avoidance.

Several case studies were used to document the cross-barrier tendencies of SLW. Some cases revealed marked temporal variability in the spatial distribution of liquid while others documented relatively steady-state conditions over periods of several hours. Numerous individual cross-barrier profiles and the average seasonal profile indicated that the maximum liquid depth occurred considerably upwind of the center of the plateau. Comparisons of mobile and stationary radiometer data also proved very useful in verifying this feature both temporally and spatially. Local topographic features, such as a minor valley and ridge on top of the plateau, influenced cloud liquid development, but the general trend of liquid depth to decrease from west to east was most likely due to removal by growing precipitation: particles, the lack of vertical motion over the plateau top and downward motion upwind of the eastern edge of the plateau due to a westward tilted mountain wave. The removal by precipitation was supported by data that showed seasonal precipitation maxima downwind of liquid maxima. The depletion of water across the top of the plateau has cloud seeding implications, in that a radiometer positioned on the windward slope or near the west edge of the top will likely overestimate the supercooled water that is available for precipitation augmentation by cloud seeding. The relatively infrequent number of observations across the plateau top warrants further observations to verify the general decrease in cloud liquid.

With knowledge of cloud base height and temperature, the mobile radiometer measurements were found to be useful in developing estimated vertical profiles of cloud liquid. The adiabatic assumption used will not characterize the typical precipitating storm situation, but the average estimated cloud thicknesses agreed relatively well with the "mean" conditions during one aircraft flight and with earlier lidar-radiometer studies on another mountain barrier in Utah. The cloud seeding implications in both regions were similar; supercooled liquid was often available, but the temperatures in the lower cloud layer were generally warm compared to the activation temperature of the silver iodide compound used in Utah. The profiles also demonstrated the need for cloud seeding aerosols to be delivered to liquid zones as far upwind as possible to increase the probability of particle trajectories terminating on the plateau.

This study represents one application of the mobile radiometer platform. Additional work is planned for the use of the data in verification of three-dimensional cloud model results for the Wasatch Plateau region and more detailed water budget studies for this mountain barrier, using a two-radiometer method.

8.16. Super, A. B., 1995a: *Case studies of microphysical responses to valley-released operational AgI seeding of the Wasatch Plateau, Utah*. *J. Weather Modification*, 27, 57-83.

ABSTRACT

An experimental field program was conducted on the Wasatch Plateau of central Utah in early 1991. Objectives included monitoring of the transport and dispersion of valley-released silver iodide and associated microphysical effects within the seeded clouds. Silver iodide ice nuclei were monitored by acoustical ice nucleus counters in a truck, an aircraft and at a Plateau-top observatory. An aircraft-mounted ice particle imaging probe was used to search for ice particle concentration differences between the seeded cloud and crosswind, nonseeded cloud. Other instruments monitored wind, cloud liquid water content, temperature and other parameters of interest.

Six experiments are described in detail, representing all aircraft sampling period during which valley-released AgI (silver iodide) was transported to both Plateau-top and aircraft altitudes. Embedded convection was present during five of the experiments which probably enhanced vertical AgI transport. Cloud bases were generally a few hundred meters below the Plateau top with one exception which had bases above the Plateau. The valley-released AgI consistently had a pronounced vertical gradient above the Plateau. Concentrations of AgI ice nuclei, effective at -20°C , were typically at least an order of magnitude less at lowest aircraft altitudes than found on top of the Plateau. Silver iodide was seldom detected as high as 1 km above the Plateau top.

No evidence was found for enhanced ice particle concentrations at aircraft altitudes during the three experiments with sampling zone temperatures of -9°C and above. However, suggestions of increased ice particle concentrations were found when sampling zone temperatures were colder. Silver iodide ice nuclei estimates, effective at prevailing supercooled liquid cloud temperatures, were lower than believed desirable for effective seeding during the three experiments with warmer cloud at aircraft sampling altitudes.

The results presented are believed to indicate that current operational cloud seeding in Utah produces insignificant increases in ice particle concentrations and snowfall rates during warmer storm episodes. The main problem appears to be that concentrations of effective ice nuclei are too low for the typical mildly supercooled liquid water clouds reached by the AgI. Seeding appeared to markedly increase the ice particle concentration in colder supercooled clouds, and precipitation observations suggested associated limited snowfall increases during some cases. A number of recommendations are made for increasing ice particles concentrations in the warmer supercooled liquid clouds.

SUMMARY AND CONCLUSIONS

Six early 1991 seeding experiments were examined in which AgI, released from a network of eight valley generators, was observed over the Wasatch Plateau of central Utah. These experiments, corresponding to aircraft sampling periods over the Plateau, were selected as all available cases with valley-released AgI detected at aircraft altitudes over the Plateau. Therefore, these cases are not representative of valley seeding in general. Valley-released AgI was not transported to Plateau top and aircraft altitudes during some other early 1991 sample periods (e.g., Super and Holroyd, 1994; Super, 1994).

All the storm periods reported herein had SLW cloud over the Plateau as measured by microwave radiometer and aircraft, although amounts were very limited in the coldest experiment and the SLW was well above the Plateau top during another experiment. Five of the experimental periods had embedded convection present. The sixth period, the coldest storm sampled during 1991, experienced passage of a mesoscale feature which may have aided transport over the Plateau.

Silver iodide IN were measured by NCAR acoustical IN counters in an aircraft, in a 4-wheel drive vehicle and at a fixed site near the head of a major canyon. Concentrations of AgI IN, effective at -20°C in each NCAR counter's cloud chamber, were often hundreds per liter at the fixed site and along the upwind highway following the Plateau top's windward edge for a 6.7 km north-south distance. Concentrations at lowest aircraft sampling altitudes were typically over an order of magnitude less than along the Plateau top. These measurements indicate a consistent, rapid decrease in valley-released AgI IN concentrations with height above the Plateau. Little AgI IN were found as high as 1 km above the Plateau top, and the aircraft sometimes overflowed the plume while within 600 m of the Plateau top.

The evidence available suggests it is reasonable to assume that ground-released AgI is seldom transported as high as 1 km above the Plateau. This is in agreement with earlier observations over other mountain barriers. Because cloud temperatures are usually only slightly supercooled in this shallow seeded layer, the challenge is to produce enough AgI IN, effective at slightly supercooled temperatures. An abundance of observations exists in the intermountain West to demonstrate that the lowest kilometer over mountain barriers is often too warm for significant nucleation with conventional types of AgI and generators, and typical release rates. The problem is even more serious in the Sierra Nevada, which led the State of California to investigate propane seeding (Reynolds 1991).

Aircraft 2D-C probe measurements of IPC were examined for possible microphysical changes associated with the AgI seeding. NCAR counter observations were used to estimate the average positions of the AgI plume (or, more likely, intermingled plumes), and in-plume IPCs were compared with natural IPCs crosswind from the AgI.

The main findings of the six previously described experiments are summarized in Tables 1 and 2. NCAR counter measurements and a recent cloud simulation laboratory generator calibration were used to estimate AgI IN concentrations effective at in-plume aircraft sampling temperatures in Table 1. The most important and reliable values in Table 1 are the IPC increases based on observed differences in 2D-C particle imaging probe measurements within and crosswind from seeded zones.

Table 1 shows increases for both the estimated AgI IN concentrations and the observed IPC enhancements as the seeded zone temperatures decreases. No discernable increase occurred in seeded zone IPC in the first three experiments where temperatures were no colder than -9°C . Valley seeding during the first experiment of 2 March may have increased the IPC. The second experiment of 2 March and the single experiment of 6 March both strongly suggest IPC enhancements within the seeded zone. The 6 March case showed IPC increases from both terrain-following and constant altitude passes. The two experiments with apparent IPC increases had the coldest clouds, below -12°C at aircraft sampling altitudes.

Table 1.—Summary of results for six valley seeding experiments. All values are averages for the seeded zone. The IPC calculations ignored particles smaller than $100\text{ }\mu\text{m}$ size.

MMDD/Exp.	Temp. range ($^{\circ}\text{C}$)	Ave. Plume width (km)	Est. AgI IN conc. (L^{-1})	2D-C IPC increase (L^{-1})
0228/1*	-5 to -9	20.6	0.05	0
0301/1	-6 to -9	30.8	0.3	<0.2
0301/2	-6 to -9	25.2	3	<0.5
0302/1	-9 to -12.5	36.2	15	<7
0302/2	-12.5	4.7	70	>14
0306/1	-15 to -18.5	25.6	70	10
0306/1	-19	10.2	60	27

* Most aircraft AgI IN observations were made below cloud base.

The AgI IN estimates in Table 1 and the estimates of seeding-caused IPC are in reasonable agreement when it is recognized that not all available AgI IN will nucleate ice crystals, especially when cloud LWC is limited. The type of AgI used is expected to result in contact nucleation, a slow process. The degree of agreement between AgI IN and IPC in Table 1 may be fortuitous. Instrumentation limitations and the uncertainties in the representativeness of cloud chamber generator calibrations result in lack of precision

for the AgI IN estimates. Estimates of seeding-caused IPC are also approximations, but should be significantly more accurate than the AgI IN estimates.

None of the estimated average AgI plume widths of Table 1 are as wide as the 40 km north-south extent of the AgI generator network. The median plume width Table 1 is 25 km, suggesting that either some of the individual generator plumes were not transported over the Plateau or that the aircraft were simply overflying some plumes. The latter case is suspected to be most common because the generators were all located in similar valley floor locations. Moreover, observations along the upwind highway indicated that when AgI was transported over the Plateau, it usually was found all along the 6.7 km north-south extent of the highway. These highway observations suggest that AgI from multiple generators was usually transported over the Plateau when any Plateau-top transport was occurring.

Observations from the network of 5 precipitation gauges could not be expected to be conclusive regarding the effectiveness of seeding since only a limited number of non-randomized experiments were conducted. However, the gauge observations may be suggestive and they do not set upper limits on possible snowfall enhancement. No seeding effects would be expected at gauges FVC and HAS on the Plateau's western slope.

The gauge observations given in Table 2 do not provide evidence of significant seeding-related snowfall increases on top of the Plateau during two of the six experiments because hardly any snow fell. Little AgI IN reached the high-based SLW cloud of 28 February so no significant response to seeding would be anticipated. Limited snowfall rates may have been caused by seeding during some of the other experiments, each of which had cloud base located below the Plateau top. Seeding may have increased snowfall particularly during the first experiment of 2 March and the single experiment of 6 March. But any enhancement of snowfall rates was limited, especially on 6 March as shown by the average hourly rates in Table 2.

Table 2.—Summary of precipitation network measurements during six early 1991 experiments from west to east over the Plateau. Values are average hourly precipitation rates in mm h⁻¹ for the indicated time periods. The times correspond to the aircraft sampling periods lagged by 15 min.

MMDD/Exp.	MST	FVC	HAS	DOT	PTC	PTE
0228/1	1345-1635	0.0	0.0	0.0	0.0	0.0
0301/1	1140-1425	0.18	0.18	0.37	0.46	0.69
0301/2	1700-1845	0.29	0.87	1.60	0.73	0.73
0302/2	1030-1125	0.28	0.55	1.79	1.10	0.69
0306/1	1315-1445	0.0	0.0	0.17	0.0	0.17
0306/1	1635-1930	0.0	0.0	0.26	0.13	0.09

The minor snowfall amounts of the second experiment of 2 March raise special cause for concern. Supercooled liquid water amounts were relatively abundant as measured by microwave radiometer and an aircraft probe. Further, the mission was terminated early because of aircraft icing. Relatively high AgI IN concentrations were transported up to aircraft altitudes where clouds were certainly cold enough for nucleation of much of the AgI. A noticeable increase in IPC resulted in the seeded zone. However, in spite of the apparently quite seedable conditions and transport of AgI to aircraft altitudes, the valley seeding did not result in significant snowfall on the Plateau top.

8.17. Super, Arlin B., 1995b: *Observations of microphysical effects of liquid propane seeding on Utah's Wasatch Plateau during early 1995. Appendix E of Bureau of Reclamation Research Report R-95-12, Bureau of Reclamation, Denver, CO, 109-133.*

INTRODUCTION

A series of limited cloud seeding experiments was conducted from December 13, 1994, through March 11, 1995, on the Wasatch Plateau (hereafter Plateau) of central Utah. The primary purpose of the experiments was to investigate the ability of AgI (silver iodide) to create significant ice particle concentrations within orographic (mountain-induced) cloud at slightly supercooled temperatures. However, a secondary purpose was to document microphysical effects of high altitude liquid propane seeding. The evidence obtained from a limited number of liquid propane seeding experiments is the subject of this report.

The experiments were simple in design. Liquid propane was released in 1-h "pulses" from a single HAS (High Altitude Site) on the Plateau's windward (west-facing) slope. Microphysical effects of the propane seeding were observed at a fixed downwind site (the Target) on the Plateau's top west edge. Both sites are indicated on Figure E.1. Instruments at the Target permitted verification that propane-seeded cloudy air passed by the Target, and permitted monitoring of ice particle characteristics before, during, and after each passage of seeded air (each pulse). Various instrumentation at both sites provided supporting measurements of wind, air temperature, and the presence of SLW (supercooled liquid water).

(Figure E.1 not included here)

SUMMARY AND RECOMMENDATION

The IPC observations during the second experiment of March 11th, taken together with those from March 5th, both argue for improved field documentation of propane effectiveness, especially at temperatures above -5°C where AgI is believed ineffective. It may be that higher propane release rates are appropriate for slightly supercooled temperatures. There is no doubt that propane seeding can increase snowfall at such temperatures when excess SLW is available. The questions yet to be answered are what release rate is required to produce significant snowfall, and is such a release rate economical? The potential importance of being able to seed slightly supercooled cloud, which is found in abundance, especially in California but throughout the intermountain West as well, is too great to ignore these questions.

The approach used in these experiments can provide valuable information to partially address the effectiveness of propane seeding. It is recommended that several additional propane seeding experiments be conducted on the Plateau between the HAS and the Target. These experiments are simple and economical, and targeting of the Target site is routine with southwesterly flow. Future experiments of this type should concentrate on periods with no more than very light natural snowfall. It is usually not possible to detect microphysical changes caused by seeding during higher natural snowfall rates because of the variability of such snowfall.

8.18. Super, A. B., E. Faatz, A. J. Hilton, V. C. Ogden and R. D. Hansen, 1995: A status report on liquid propane dispenser testing in Utah with emphasis on a fully-automated seeding system. *J. Weather Modification*, 27, 84-93.

ABSTRACT

Liquid propane dispensers were tested on the Wasatch Plateau of central Utah during the winters of 1992-93 and 1993-94. Remote operation of the radio-controlled dispensers proved to be highly reliable, in large part because of the mechanical simplicity of the devices. A prototype fully-automated liquid propane seeding system was tested during early 1994 on the west (windward) slopes of the Plateau. An icing rate device was used to detect supercooled liquid water at the center station of three exposed propane dispenser stations. Wind speed and direction and air temperature were also monitored at the center station. When certain predetermined weather criteria were met, the three propane dispensers were automatically turned on. Propane continued to be dispersed until one of more of the weather criteria were out-of-bounds for 2 h.

Post season analysis of recorded data showed that the fully-automated seeding system operated as designed for the most part. Some minor problems were encountered, but can easily be corrected. Recommendations are made for simplifying the automated decision process.

A means of detecting supercooled liquid water in the absence of commercial electrical power was also tested during early 1994. It proved to be practical and reliable. Accordingly, the technology exists to operate fully-automated networks of liquid propane dispensers in remote mountain locations. Costs of such networks would not be excessive, and reliability can be expected to be high. However, further physical experimentation is recommended to document the effectiveness of liquid propane seeding for snowfall enhancement because such evidence is quite limited.

SUMMARY AND RECOMMENDATIONS

A propane dispenser was tested during the 1992-1993 winter, well up the west slope of the Wasatch Plateau east of Fairview, Utah. The dispenser was based on the design of Reynolds (1989, 1991), with some modifications. The dispenser was turned on and off by a data logger/controller upon receipt of appropriate radio signals from a valley base stations. Human intervention and a computer were used to initiate the radio signals. Various data were logged at the site and periodically downloaded to the base station.

A technician was often at the dispenser site, monitoring its operations, while a second technician turned the system on and off. These visual observations helped to confirm the very reliable operation of the propane dispenser.

Further testing was done during early 1994, in two different modes. In the first mode, two dispensers were used during physical seeding experiments with system start-up and shutdown done as in the prior winter (human intervention, radio telemetry and computers). The physical seeding experiments have yet to be analyzed and reported, but dispenser operation was again very reliable.

The second testing mode involved a prototype seeding system which was automatically turned on and off according to weather observations. The weather (SLW, wind and temperature) was monitored at a central

dispenser. That dispenser, and two satellite dispensers, were controlled by the presence/absence of SLW, wind measurements, and (redundant) air temperature observations.

The automated seeding system had some problems, but they are considered minor and easily correctable. The system generally functioned very well, especially considering that no visits were made to the dispensers once testing started. Some improvements should be made in the data logger program. A more rigid holder for the propane stream temperature sensor would eliminate the cycling problem experienced by the Bald Mountain dispenser.

It is recommended that future use of an automated propane dispenser system use simplified criteria. The presence of SLW would continue to be measured by a Rosemount icing rate device well up the windward slope. Seeding would commence as soon as the first Rosemount cycle occurred. Seeding would continue for some time (about 2 h) after the last Rosemount cycle in an episode. Wind speed and direction could be monitored but are not believed essential because SLW rarely occurred unless wind speed and direction were appropriate for targeting the Wasatch Plateau. (It is anticipated that most north-south oriented mountain ranges would experience similar conditions.) Some propane would be released during essentially unseedable conditions if only SLW presence/absence was used to control seeding. However, the amount of wasted propane is expected to be minor.

A thermoelectric generator-battery-inverter combination, as used at the HAS in early 1994, is a practical means of powering a Rosemount icing rate device, a data logger/controller, a propane dispenser and radio gear at an exposed remote location in all weather conditions. This system could be the master station controlling a number of satellite dispensers located at similar high altitude sites crosswind of the master station. All sites should be chosen where local SLW production is expected. If one wanted to be sure that SLW existed at each dispenser, each site could monitor SLW with a Rosemount device. This would be a superior but more costly approach.

Propane dispenser testing in California and Utah in recent years has demonstrated the feasibility of a completely automated system that is both reliable and economical. Analysis of the early 1994 physical seeding experiments should improve understanding of the snowfall-enhancing capability of propane seeding. Prior research leaves no doubt that propane seeding can markedly enhance ice crystal concentrations with liquid cloud at or below 0 °C. However, it is recommended that the ice crystal yield of the currently-used (in Utah) propane nozzle and release rate be documented. The previously-cited yield values of 10^{11} to 10^{12} ice crystals per gram of propane are based on investigations done over two decades ago. These studies used different release rates and nozzles than recently used in California and Utah. It is of obvious interest to test the current design to determine whether yield value are as high as expected.

Additional key questions to be answered concern ice crystal growth and fallout times downwind of propane dispenser sites. To be effective, propane dispensers need to be within SLW cloud, or at least not far below SLW cloud base where saturation with respect to ice exists. This requires that dispensers be located well up the windward slopes of mountain barriers. Such siting limits the time (distance) available for ice crystal growth to snowflake sizes and fallout to the mountain surface. There is concern that this time (distance) may frequently be too limited for significant snowfall to occur before the seeded ice crystals are carried into the lee subsidence zone where sublimation and evaporation occur.

Another concern with high altitude releases of propane (or AgI) is that crosswind dispersion may be limited, requiring that the crosswind spacing of generators also be limited to avoid unseeded "gaps" between seeding plumes. It may be possible to have greater spacing between AgI generators located further down slope or in upwind valleys thereby requiring fewer seeding sites. Of course, use of lower

altitude sites assumes adequate routine transport from them into SLW cloud zones as well as adequate source strengths.

It is recommended that analysis of the early 1994 microphysical observations, and additional future observations, be combined with numerical modeling to address the above concerns. A sophisticated microphysical model, combined with a two or three dimensional airflow model, should be adequate to address ice particle growth and fallout trajectories.

It may be that only relatively wide mountain barriers offer sufficient time and distance for propane seeding to routinely affect snowfall on that barrier. In that case, the best use of high altitude propane seeding may be in seeding a secondary downwind barrier similar to the Bridger Range Experiment target (Super and Heimbach 1983). In any event, the frequency of orographic SLW cloud at temperatures too warm for AgI nucleation is significant over mountains of the western U.S. That fact alone argues for continued experimentation with alternative seeding methods such as release of liquid propane which might augment AgI seeding when slightly supercooled clouds are present.

1996 articles and papers:

8.19. Griffith, D. A., 1996: *Potential application of results from the NOAA atmospheric modification program to the conduct of a Utah winter orographic cloud seeding program. 13th Conference on Planned and Inadvertent Weather Modification, Atlanta, GA, American Meteorological Society, 118-120.*

INTRODUCTION

An operational winter orographic cloud seeding program has been conducted in Utah in most winter seasons since 1973-74 (Griffith et al., 1991). This program utilizes networks of valley based silver iodide generators that are selectively turned on and off during the passage of winter storms through the State of Utah. Generators are sited upwind of target mountain barriers and are operated upon instruction from North American Weather Consultants' (NAWC) meteorologists, located in Salt Lake City. The goal of the program is to augment mountainous snowfall for subsequent use for irrigation and municipal water supplies. The program is funded by counties, water conservancy districts and the State of Utah, Division of Water Resources.

BACKGROUND

The design of the Utah operational cloud program is based upon the results of earlier research programs (i.e., Climax, Colorado River Basin Pilot Project). Three general hypothesis constitute the conceptual model for the program.

- Sufficient supercooled liquid water is present in winter storms over Utah to permit seeding material to nucleate and grow additional precipitation sized hydrometeors.
- Silver iodide seeding material released from ground generators can reach seedable locations in sufficiently dilute but wide-spread concentrations to affect a significant portion of a storm.

- Growth times and trajectories of natural and augmented precipitation sized hydrometeors are appropriate to intercept the intended target area.

Target/control evaluations of the effectiveness of the Utah operational cloud seeding program have indicated apparent increases in target area precipitation in the range of 10 to 15 percent (Griffith, et al., 1991). Recent application of Monte Carlo techniques to these evaluations indicate the results are significant.

APPLICATION OF PROGRAM

These results support the first of the three conditions listed in the Utah conceptual model (Background). This is an important verification of what was assumed to be true of Utah storms based upon observations made in other geographical areas.

Transport of valley-released silver iodide/SF₆ over Utah mountain barriers has been documented. Since the supercooled liquid water is predominately located at low level on the upwind slopes of mountain barriers and the generators are located in valleys upwind of these barriers, the silver iodide nuclei are encountering the preferred supercooled liquid water formation zones. This is also an important result related to the second part of the Utah conceptual model (Background). In some cases valley-released silver iodide/SF₆ is not transported over the mountain barrier. These cases generally occur when there are low level atmospheric inversions. An interesting observation on some cases indicate nuclei "pool" under these conditions which are sometimes subsequently scoured from the valley and transported over the barrier with the passage of a synoptic feature. This may suggest that valley generators should be operated under trapping inversions ahead of the passage of synoptic features. NAWC seeding criteria have typically precluded operations under these conditions.

Location of manually operated ground generators at the mouths of canyons on the windward slopes of target barriers may offer a preferred location for transport of silver iodide nuclei over the barrier when transport from valley locations is ineffective.

The plume spread from ground based releases of silver iodide and SF₆ (15 to 25°) suggest that generators should be located at a spacing of 4 to 5 km apart upwind of the barrier in order to achieve plume overlap. The spacing currently used on the Utah operational program is on the order of 16 km.

Remotely controlled generators may be effective during periods when valley based generators are not effective. The addition of such generators in high yield, high water value locations would offer an improvement to the current Utah operational program. Such operations are substantially more expensive than valley based networks thus the restriction of such remote generators to high yield/high water value target locations. NAWC has installed manually operated silver iodide generators at higher elevation areas where local residents can be located to operate the units.

The improvement in efficiency of the NAWC manual silver iodide generator, as documented in the CSU tests, is an important result. The supercooled liquid water detected in Utah winter storms is frequently in the 0 to -10 °C range. It is in the -6 to -10 °C range that the recent CSU tests indicated improved efficiency over earlier tests.

Information from the Utah AMP suggest higher concentrations of seeding material are desirable. A change from a 2% to a 3% by weight mixture of silver iodide in acetone along with the denser spacing of seeding generators would provide a means of increasing these concentrations.

8.20. Heimbach, J. A., and W. D. Hall, 1996: Observations and modeling of valley-released silver iodide seeding over the Wasatch Plateau. 13th Conference on Planned and Inadvertent Weather Modification, Atlanta, GA, American Meteorological Society, 31-37.

ABSTRACT

This paper examines the transport of surface-released silver iodide (AgI) over the Wasatch Plateau of central Utah during inversion conditions. Other case studies of transport have been reported for the Wasatch Plateau. For example, Super and Huggins describe targeting of valley- and canyon-released AgI in an analysis of surface observations (1992a) and aircraft observations (1992b) from the 1989-90 field season. Surface silver-in-snow and real-time ice nucleus (IN) measurements indicated that AgI was transported up the canyon over the Wasatch Plateau but in limited amounts. Co-released sulfur hexafluoride SF_6 was detected by the aircraft for one of five flights. These two papers highlighted the difficulty in targeting seeding material. Heimbach and Hall (1994) modeled various release configurations in a case which had neutral stability and no imbedded convection. They found transport of seeding material over the Plateau also demonstrated that downwind depletion of liquid water (LW) was at least in part due to subsidence warming within a gravity wave pattern. Holroyd et al. (1995) reported on the analysis of the 21 February 1994 experiment which had weak surface winds, light snowfall and weak convection in thin orographic clouds over the Plateau. On this date AgI and SF_6 were co-released from a site part of the way up the windward side of the Plateau. A microphysical seeding signal was associated with the IN plume both at the surface and aloft. Modeling results of transport were reasonably close to observations for this case. Bruintjes et al. (1995) applied the Clark model to three cases from the 1987 Arizona/NOAA Cooperative program. Each of these had a single point-source of SF_6 . Results from field observations and the model led them to conclude that the transport and diffusion of seeding material are dependent upon the flow and stability conditions around the valley release site, and gravity waves stimulated by the upwind terrain.

DISCUSSION

The transport of AgI released from three valley sites was examined for an experiment conducted on 7 February 1994. Sulfur hexafluoride was also released on this date from the mouth of a canyon located on the windward side of the Plateau. The observations indicated transport of the AgI over the Plateau mostly within a shallow layer in spite of being released in a stable surface layer with weak and sometimes easterly winds.

At the RRS and TAR site, concentrations of 100 in L^{-1} , effective at -20°C , were commonly sampled. The temperatures at these sites were approximately -6°C . The IN effectiveness of the generators and solution used in the valley is 2.5 orders of magnitude less for -6°C (DeMott et al., 1995), giving an effective concentration of 0.24 IN L^{-1} . There were, however, periods having concentrations of several thousand per liter effective at -20°C suggesting concentrations on the order of 5 L^{-1} . No IN or SF_6 plumes were detected over the W track. The only significant IN plume detected by the aircraft was over the E track in the vicinity of the TAR site at 3.5 km MSL (minimum IFR elevation). For the acoustic IN detector, indicated spread of an IN encounter is due to actual spread plus a temporal component from mixing within the cloud chamber (Heimbach et al., 1977). For this reason, estimating the peak concentration of IN at a point is risky for aircraft sampling. Adjusting for cloud chamber mixing, the maximum concentration of IN was less than 20 L^{-1} effective at -20°C . The temperature at this level was -8°C implying the maximum concentration of effective IN was less than 1.5 L^{-1} . The IN targeted zones of supercooled LW over at least some portions of the Plateau, though indications are that this was in a very shallow layer

except during a limited time for one aircraft pass over the TAR site. Later in the experiment, few IN were encountered at the surface on the Plateau.

For the present case study, the modeling suggests the valley-released AgI had an initial vertical impetus by the gravity wave mechanism which provided transport above the surface inversion. This was followed by orographic forcing in a more organized westerly flow. The model confirmed the confinement of the plume to a shallow layer and subsequent lifting due again to a gravity wave was further eastward in the vicinity of the TAR site. It may be possible to exploit the influence of gravity waves in surface-based seeding strategies. This was explored by Heimbach and Hall (1994) who applied the model to several source configurations. Super (1994) suggested that targeting might be enhanced if releases were from a mountain upwind of the Plateau (San Pitch). For the current case, we suggest that the upwind side of this barrier would be appropriate. Figure 6 also indicates that the W side of the Sanpete Valley could provide some initial upward impetus; however, the subsequent downward portion of the gravity wave could have a detrimental influence on targeting. Releases further upwind of the current valley sites have the disadvantage of greater dispersion which would reduce the concentrations over the target, and greater difficulty in horizontal targeting. Also, the increased fetch would make targeting more difficult.

8.21. Heimbach, J. A., and A. B. Super, 1996: Simulating the influence of type II error on the outcome of past statistical experiments. *J. Applied Meteorology*, 35, 1551-1567.

ABSTRACT

Simulations of randomized winter orographic weather modification experiments were used to explore a possible cause of the many inconclusive results from previous statistical experiments. There is increasing evidence that the response to cloud treatment is highly variable due to differences in the availability of cloud liquid water, seeding agents, targeting effectiveness, and other factors. For this reason the simulations described in this paper focus on the sensitivity of previously applied statistical techniques to different responses to seeding. Data for the simulations came from two sources: the Bridger Ranger Experiments (BRE), conducted during the two winters from 1970 to 1972, and SNOTEL (snowpack telemetry) data from the Boise, Idaho, area during the winters of 1985-92. The principal focus is on the BRE data from which 6-h experimental units were extracted. This is because previous analyses of these data support the notion of a variable treatment response. Twenty-four-hour experimental units from the BRE and Idaho datasets were also incorporated into the simulations.

The simulations indicate a sensitivity to the size of the fraction of seeded units, which had a treatment response with the power of the test being significantly reduced as the fraction of seeded units showing a response decreased. It is suggested that past estimates of experimental duration, based on the simple model that assumed all seeded units have the same response were overly optimistic. The results may partially explain the high frequency of inclusive results from past statistical cloud seeding experiments. The implications of these results is described for past and future statistical weather modification experiments.

Monte Carlo techniques were applied in simulations that assumed a randomized target-control experiment. There were five models applied, which involved adding a percentage or constant responses to all or a fraction of the seeded units and capping the maximum increment. Experimental units were randomly selected from a pool of nonseeded cases. The selected units were randomly seeded or not seeded, and the seeded units were again randomly selected to have all or a fraction of them show a treatment effect, while keeping the net seasonal response approximately constant. For example, in the case of one out of three

seeded units showing a treatment response, that unit would have triple the response of a simple model, which had each seeded unit showing a response. Net treatment responses were taken from the most successful partitions found for the BRE. Experimental units were added until a 0.05 one-tailed P level was achieved, where P is the probability of incorrectly concluding that there is a positive seeding effect when none exists (type I error). Each simulation was repeated 1000 times to estimate the number of experimental units needed to reach a specified power level ($1 - \beta$), where β is the probability of a type II error—the probability of not detecting a treatment response when one exists.

SUMMARY AND RECOMMENDATIONS

The main purpose of this paper is to explore how variable responses to seeding might have affected the statistical power of the test of past experiments. This was done by examining how the experimental duration might vary for winter orographic cloud seeding statistical designs that were common in the past, using different assumed responses to treatment. Most previous investigations assumed that each treated experimental unit would have the same percentage precipitation increase. Increasing evidence shows that this simple model is physically unrealistic. Seeding likely results in large percentage increases from a fraction of cases that are particularly amenable to treatment, but has little or no effect on the remaining cases. This result is likely true for other type of weather modification (rain augmentation, hail suppression), so the results in this paper may have a more general application beyond winter orographic cloud seeding.

Monte Carlo techniques were first applied to simulated experiments using nonseeded 6-h data from the BRE. Seeding response models had a percentage of precipitation increase to all or a fraction of seeded experimental units. Only the one-tailed probability level $\alpha = 0.05$ was considered in all simulations. Following the results of the exploratory statistical analysis of S for the cold partition, a net precipitation increase of 66% was approximated in each experiment. These simulations were calculated with all available nonseeded cases with main ridge temperatures of -9°C and colder and a westerly wind component at 700 hPa.

The number of units required to achieve statistical significance varied considerably with the different assumed treatment responses. For the 6-h BRE dataset, only a single winter of randomized seeding would be required to achieve $\alpha = 0.05$ with a power of 0.9 if all treated experimental units responded with a 66% increase (model I). However, if only one-sixth of the units responded, though each with a 396% increase, almost six winters of experimentation would be required to achieve the same α and power levels. Similar results were obtained with the BRE and Idaho 24-h datasets. Simulations that limited seeding responses to the smallest or null accumulations indicated that there was little likelihood of detected with an effect with confidence.

Simulations were also done in which a constant increase in precipitation amount was added to all or a fraction of seeded units partitioned by natural precipitation accumulation during the experimental period. These simulations also demonstrated a sensitivity to the character of simulated precipitation increases for all the datasets. These simulations reinforced the experimental design issues highlighted by the models I, II and III presentations: more experimental units are needed if only a fraction of treated units respond to seeding.

The simulations illustrate the importance of considering power as well as α in experimental design. Conducting a randomized seeding experiment without some physically reasonable estimate of power is very much a "crap shoot". An acceptable α level may or may not result in the time allowed for the experiment (often determined by the sponsor's patience and resources). If the desired α level is achieved,

the experimenters may have been very fortunate in the specific population of units that nature provided. But a replication of the experiment may take several times as long to complete. If the P value does not reach an acceptable α level, it may simply be that insufficient time was allowed to have a reasonable chance of achieving a significant result. That is, seeding may have been effective but was undetected because the number of experimental units was too limited (type II statistical error). The only correct conclusion is that seeding effectiveness was neither proved nor disproved.

When a serious effort is made to consider both α and power in the experimental design, the treatment response model should be carefully selected. The particular model chosen has been shown to have a large impact on estimated experimental duration. Unfortunately, present knowledge of treatment response is limited. However, model I, the most commonly used model, is likely unrealistic. Its use results in overly optimistic estimates of experimental duration.

This presents the experimenter with a dilemma. It is imprudent to design a statistical cloud seeding experiment without reasonable α and power levels. However, accurate power-level estimates may be beyond the scope of present physical understanding. The best course for future investigations would therefore be to improve physical understanding before designing more statistical experiments.

The implications of these results are sobering. They suggest that previous statistical experiments may have been handicapped by the assumption of a simplistic treatment response model, which led to overestimates of experimental power. The number of experimental units required to achieve given α and power levels may be far larger than estimated for most past experiments, which could partially explain the frequent finding of inconclusive results.

A number of points must be considered in designing future statistical experiments. First, strong predictor-covariate relationships with target area precipitation are necessary to reduce the number of experimental units needed to detect a seeding signal. Second, partitioning based on a solid physical understanding is needed to reduce the number of experimental units that have minimal or no response to seeding. Third, improved statistical techniques could be useful, but their development may be difficult in view of uncertainties of how treatment responses vary among the population of treated units. Fourth, and most important, a much improved physical understanding is needed prior to the development of any future statistical design. Over a decade ago, Braham (1981) made a strong case for improving our physical understanding before conducting any further "black box" experiments that had a major emphasis on demonstrating precipitation changes at the ground. Schaefer (1990) also argued for a better physical comprehension of the effects of cloud seeding. The results of this paper strengthen the case for improved physical understanding prior to further statistical testing of cloud seeding.

8.22. Huggins, A. W., 1996: *Use of radiometry in orographic cloud studies and the evaluation of ground-based cloud seeding plumes*. 13th Conference on Planned and Inadvertent Weather Modification, Atlanta, GA, American Meteorological Society, 142-149.

INTRODUCTION AND BACKGROUND

Since 1981 a program to evaluate the cloud seeding operations of the state of Utah has been conducted in southwestern and central Utah. The research is part of the Atmospheric Modification Program (AMP), a cooperative venture between six states, the Navajo Nation and the National Oceanic and Atmospheric Administration (NOAA). The Utah project is concerned with the modification of winter orographic cloud

systems to augment snowfall in mountainous regions, and ultimately to increase runoff in the spring and summer months.

Prior to 1990 the project focused on the evolution of supercooled liquid water (SLW) in winter storms over the Tushar Mountains. Long et al. (1990) and Sassen et al. (1990) documented the importance of synoptic, mesoscale and local topographic forcing in SLW development. Super and Huggins (1993) summarized SLW flux estimates from four seasons of microwave radiometer measurement in the Tushar Mountains and the Wasatch Plateau, finding that nearly all winter storms contained supercooled liquid water that was not being converted to precipitation augmentation potential of winter storms by comparing SLW and precipitation fluxes. All these studies found that significant snowfall augmentation potential existed, provided an appropriate cloud seeding technique could be applied at the proper time and location to convert excess SLW to ice crystals, and ultimately to snowfall.

Beginning with a field program in 1991 on the Wasatch Plateau, the Utah AMP shifted its emphasis to studies of cloud seeding aerosol dispersion from silver iodide ground-based generators in valleys upwind of the plateau, and from generators positioned partway up the windward slopes of the plateau (referred to later as high altitude generators), and to studies designed to detect the effects of seeding. Supercooled liquid water studies focused on the spatial distribution of SLW across the plateau using a new mobile radiometer technique. Huggins (1995) summarized the first mobile radiometer experiments from 1991, finding an expected maximum in SLW depth over the windward slopes, with decreasing depths across the top of the plateau due mostly to removal by precipitation. Griffith et al. (1992), Heimbach and Hall (1994), Holroyd et al. (1995), and Super (1995a) report the results of plume dispersion studies, including the modeling of plumes, and the detection of microphysical seeding effects during seeding experiments in 1991 and 1994. Aerosol plumes from high altitude and valley-based generators have been detected frequently (somewhat less frequently for valley releases) by ground-based platforms on the plateau, and by aircraft flying above the plateau.

There remains a need for further evaluation of seeding plumes, particularly to determine the frequency with which they reach appropriate altitudes (temperatures) and liquid water conditions for ice crystal nucleation by the silver iodide compound currently used in Utah's operational project. Although some indications of microphysical effects from ground seeding have now been documented, it remains to more fully quantify the impact of seeding on precipitation under various winter storm conditions.

This paper focuses on the use of the mobile radiometer, in conjunction with another ground-based mobile instrument platform, to document cloud conditions within seeding plumes, and to show further evidence of the natural depletion of SLW across the Wasatch Plateau. Results are presented for one case study where the impacts of high altitude seeding were apparently detectable on radar.

SUMMARY OF RESULTS

A multiple radiometer technique was used to demonstrate upwind/downwind differences in SLW depth, which had previously been indicated by mobile radiometer passes across the same mountain barrier. An example from 7 February indicated downwind depths averaged about 0.5 mm less than upwind depths during a two hour period of comparison over a 10 km distance. Converting this depth difference to a flux difference, and then converting the flux to a precipitation rate over the 10 km distance, indicates a 1.62 mm h⁻¹ precipitation rate would have been required to account for the difference in SLW across the plateau top.

A second case study from 26 January showed the capability of the mobile radiometer to characterize the SLW conditions within ground seeding plumes, when used in combination with aerosol detection instruments. These mobile systems are advantageous in ground-based seeding experiments, where plume dispersion and SLW development are often highly dependent on local topography, and difficult to monitor solely with aircraft. The case in this study showed that the cloud seeding plume was frequently coincident with a SLW maximum generated by a local ridge. However, at 5 km from the seeding generator there was no consistent observation of SLW depletion within the seeding plumes, possibly because the temperature was relatively warm for the AgI compound in use, and without rapid nucleation near the generator, the ice concentration from contact nucleation alone would have been relatively low.

The third study described a case where seeding plume locations were well documented at the surface and aloft. The cloud was confined to a shallow layer within about 600 m of the mountain barrier, and the seeded plume was shown to have penetrated vertically through this region. The temperatures were optimum for ice formation by AgI, and the relatively slow wind speeds allowed ample growth time for ice initiated near the upwind edge of the Wasatch Plateau. The case was marked by the appearance of a plume-shaped radar echo whose position and period of existence matched that of the seeding aerosol plume. Radar and precipitation intensities were enhanced within the aerosol/radar plume, in contrast to regions both north and south of the plume. One precipitation measurement within the plume, about 12 km downwind of the generator, exceeded 3 mm over a two hour period. This compared to a measurement of 0.6 mm outside the plume. Ice crystal microphysics measurements are expected to help determine whether these results represent a well defined seeding signatures.

8.23. Super, A. B., 1996: Two case studies showing physical effects of both AgI and liquid propane seeding on Utah's Wasatch Plateau. 13th Conference on Planned and Inadvertent Weather Modification, Atlanta, GA. American Meteorological Society, 156-163.

INTRODUCTION

Cloud seeding experiments conducted during the 1994-95 winter on the Wasatch Plateau (Plateau) of Utah investigated the ability of silver iodide (AgI) to create a significant ice particle concentration within orographic (mountain-induced) cloud. AgI ice nucleation has been investigated in laboratories, but orographic cloud characteristics raise questions about laboratory results. Laboratory clouds have higher droplet concentrations and liquid water contents, are more homogeneous, and have less turbulence.

The experiments also documented microphysical effects of high altitude liquid propane seeding. Published results of propane effectiveness (Hicks and Vali 1973; Kumai 1982) show enough variability to justify further field testing, especially at temperatures above -5 °C where AgI is expected to be ineffective.

AgI or liquid propane was released in 1-h "pulses" from the High Altitude Site (HAS) at 2540 m elevation on the west-facing Plateau slope. The site is exposed to winds from south through west as elevations decrease rapidly with distance. Microphysical effects of propane seeding were observed at the Target on the Plateau top's west edge at 2855 m, 4.2 km northeast of the HAS. Instruments verified that seeded cloudy air passed by the Target and monitored ice particle characteristics before, during, and after each passage of seeded air (each pulse). Instruments at both sites provided measurement of wind, air temperature, and presence of supercooled liquid water.

SUMMARY AND RECOMMENDATION

The seeding experiments produced obvious changes in microphysical characteristics and snowfall during periods with very limited natural snowfall. One of these experiments used an AgI release while HAS and Target cloud temperatures were near -9.0 and -10.7 °C. The resulting seeded IPC and snowfall was estimated at 140 L^{-1} and 1.0 mm h^{-1} , respectively, 4.2 km east-northeast of the HAS at the Target.

The second experiment released liquid propane at HAS cloud and Target temperatures of -3.3 °C and -4.5 °C, respectively. Propane seeding was estimated to have enhanced IPC by about 30 L^{-1} and snowfall by 0.25 mm h^{-1} . Higher propane release rates may be appropriate for these slightly supercooled temperatures.

A third experiment with AgI seeding conducted after the second did not enhance IPC during temperatures near -2.5 °C at the HAS and -4.0 °C at the Target. These experiments have provided valuable information to partially address seeding effectiveness. Additional seeding experiments should be conducted on the Plateau between the HAS and the Target. These experiments are simple and economical, and targeting of the Target site is routine with southwesterly flow at the HAS. Future experiments of this type should concentrate on periods with no more than very light natural snowfall. Detecting microphysical changes caused by seeding during higher natural snowfall rates is difficult because of the variability of such snowfall.

1997 articles and papers:

8.24. Cripps, D., and B. Abbott, 1997: *The use of capacitance to detect icing. J. Weather Modification*, 29, 84-87.

INTRODUCTION

The Utah State Division of Water Resources currently operates several cloud seeding sites in the Utah mountains. The sites use icing probes to detect supercooled liquid water; the presence of which indicates favorable conditions for cloud seeding. Propane is released into the atmosphere when supercooled liquid water is present providing refrigeration which freezes existing water droplets leading eventually to precipitation. Accurate sensing of ice, and thus the presence of supercooled liquid water is critical to efficient use of resource in this process.

Currently, icing probes designed for the aerospace industry are used to detect the presence of supercooled water. The probe consists of a vibrating rod which is extended into the atmosphere and ice build up on the rod causes the frequency of vibration to shift. It is this shift of frequency that is detected and processed to control propane release. When icing is detected, the decision to release propane is made, and then the current build up of ice on the probe is melted off and the detection cycle begins again. Propane is released continuously after icing is detected until an ice free cycle occurs.

The probes in use are expensive, require an AC power source, and have moderately high power requirements. The cost and power requirements of these probes prohibit widespread development of cloud seeding sites. This paper presents research on an alternative icing probe based on a capacitive measure of icing conditions. Research on this icing sensor is being sponsored by the Utah State Division of Water Resources.

CONCLUSION

Development of an ice sensing system using capacitive icing probes shows promise in that such a system may prove to be an inexpensive and reliable alternative to icing probes currently in use. Preliminary tests has given favorable results and have encouraged further capacitive probe/ice sensing system development. Development is now focused on probe shape and ice/melt water shedding capabilities.

8.25. Heimbach, J. A., W.D. Hall and A.B. Super, 1997: *Modeling and observations of valley-released silver iodide during a stable winter storm over the Wasatch Plateau of Utah. J. Weather Modification*, 29, 33-41.

ABSTRACT

An experiment was conducted over Utah's Wasatch Plateau which, due to stable conditions, resulted in unexpected transport of silver iodide (AgI) and sulfur hexafluoride (SF_6) tracer gas from valley floor and canyon mouth locations. The AgI ice nuclei (IN) and gas were transported vertically more than 1 km above the valley release sites in spite of the existence of a valley-based inversion beneath a saturated pseudo adiabatic layer. The Plateau top was well-targeted by IN at the surface; however, few IN were found at aircraft sampling levels. The SF_6 was poorly targeted, with most of the surface penetrations by a mobile sampler being in the valley or in a canyon accessible by highway north of the release point. There were only three small airborne penetrations of the SF_6 .

The four-dimensional mesoscale model of Clark and associates was applied to this case. The model showed generally a good agreement with the field observations and offered some insight into the manner in which the tracer material was transported over the Plateau. The model suggests that the AgI was initially transported from the surface through the inversion by the gravity wave mechanism, whereas the SF_6 likely had a limited initial vertical impetus through anabatic motion.

DISCUSSION

The transport of AgI released from three valley sites was examined for an experiment conducted on 7 February 1994. Sulfur hexafluoride was also released from the mouth of a canyon located about 1.5 km east of the northern-most AgI generator. The observations indicate transport of the AgI over the Plateau despite its being released in a stable surface layer with weak and sometimes easterly winds.

At both the RRS and the TAR Site, concentrations of 100 IN L^{-1} were commonly sampled with the acoustical IN counter, effective at -20 °C. The temperatures at these sites were approximately -6 °C. The IN effectiveness of the generators and solution used is 2.5 orders of magnitude less at -6 °C than at -20 °C (DeMott et al. 1995), giving an effective concentration of only 0.24 IN L^{-1} at the Plateau-top sites. There were, however, periods having concentrations of several thousand per liter effective at -20 °C suggesting effective concentrations on the order of 5 L^{-1} .

No IN or SF_6 plumes were detected by the aircraft on the west track which could sample no lower than 300 m above ground level. The only significant IN plume detected aloft was over the east track in the vicinity of the TAR Site up to 3.5 km MSL (minimum IFR elevation). For the acoustic IN counter, the indicated spread of an IN encounter is due to actual spread plus a temporal component from mixing within the cloud chamber (Heimbach et al. 1977). For this reason, estimating the peak concentration of IN at a

point is difficult for aircraft sampling. Adjusting for cloud chamber mixing, the maximum aircraft-measured concentration of IN was less than 20 IN L⁻¹ effective at -20 °C. The temperature at this level was -8 °C, implying the maximum concentration of effective IN was less than 1.5 L⁻¹. Zones of SLW over the Plateau were targeted by IN, though indications are that this was in a shallow layer. Later in the experiment, IN concentrations on the Plateau were reduced to near-background levels.

For the present case study, modeling suggests that the valley-released AgI had an initial vertical impetus by the gravity wave mechanism which provided transport above the surface inversion. This was followed by orographic forcing in a more organized westerly flow. The model confirmed the confinement of the plume to a shallow layer and subsequent lifting again due to a gravity wave further eastward in the vicinity of the TAR site.

It may be possible to exploit the influence of gravity waves in surface-based seeding strategies. This was explored by Heimbach and Hall (1994) who applied the model to several source configurations. Super (1994) suggested that targeting might be enhanced if releases were from a barrier upwind of the Plateau, in this case the San Pitch Mountains. Targeting from high altitude releases is generally successful provided there is an organized cross-barrier wind component. On the other hand, valley releases have uncertainties in terms of reaching the target and doing so in sufficient concentrations (*ibid*). Therefore, the gravity wave mechanism would be best exploited with valley releases which can "load" an entire valley floor with high IN concentrations. The wave structures can be wide ranging depending on speed and stability, making a broad source area or pool of aerosol advantageous. Seeding from the valley sites could not take advantage of fast-acting forced-condensation nuclei (Finnegan and Pitter 1988) because the temperatures are frequently above -6 °C (Li and Pitter 1997). Therefore, a contact nucleant would be appropriate provided the gravity wave mechanism contributed to a deep enough lifting to reach sufficiently colder temperatures.

The criteria for judging the possibility of gravity wave excitation are uncomplicated: (1) a cross-barrier wind component exists, and (2) the atmosphere is stable. For the latter, this implies potential temperature increases with height which includes moist adiabatic profiles commonly observed in project soundings. A more objective criteria can be devised using the Froude number, *Fr*. This is a nondimensional ratio of vertical perturbation to horizontal wind speed,

$$Fr = v h / U, \quad (2)$$

where *U* = cross-barrier wind speed, *v* = the Brunt-Vaisalla frequency (Eq. 1), and *h* = the height of the barrier. Gravity waves are stimulated when *Fr* < 1 (Bruinjes et al. 1995), a criteria easily tested with a sounding. For Froude numbers between 1 and 2, high amplitude waves can be formed over the lee slope of a barrier (Smolarkiewicz and Rotunno 1989). This suggests that for low wind speed and high stability conditions, the lee of the San Pitch Mountains could be a reasonable release zone. However, dilution, the subsequent downward portion of the wave and horizontal targeting issues complicate this application. For the current case, Fig. 6 suggests that the upwind side of this barrier would be appropriate.

Super (1995a) suggests the Utah operational network in the Sanpete Valley, though sometimes successful at targeting the Plateau, often provided low concentrations effective at the ambient temperatures. Effective targeting would require a strong source configuration with many more generators and/or higher output generators. Figure 6 also indicates that the west side of the Sanpete Valley could provide some initial upward impetus; however, the subsidence portion of the gravity wave could have a detrimental influence on targeting. Releases further upwind of the current valley sites have the disadvantage of

greater dispersion which would reduce the concentrations over the target, and greater difficulty in horizontal targeting.

8.26. Super, A. B., and E. W. Holroyd, 1997: *Some physical evidence of AgI and liquid propane seeding effects on Utah's Wasatch Plateau*. *J. Weather Modification*, 29, 8-32.

ABSTRACT

A series of cloud seeding experiments were conducted on Utah's Wasatch Plateau during the winter of 1994-95. Their purpose was to permit physical assessment of the effects of both silver iodide and liquid propane seeding, particularly at only slightly supercooled temperatures. Seeding materials were released in 1-hour pulses from a location well up the plateau's windward slope. The terrain often channeled the seeding plumes to an observing site, or target, located at a canyon head on the plateau top's upwind edge. Snow particles were detected at the target with a vane-mounted 2D-C optical array probe whose strobing speed was governed by an anemometer. AgI nuclei were detected there by an NCAR ice nucleus counter to confirm the presence and successful targeting of seeding materials.

Seeding with AgI under cold conditions produced obvious large increases in ice particle concentrations and measurable increases in precipitation at the ground during one experiment. Seeding with AgI under only slight supercooled conditions, in which the contact-freezing mechanism is not expected to be effective, typically produced a negligible ice particle supplement. A forced condensation-freezing mechanism may have been operable during two experiments, producing detectable enhancements in the ice particle concentrations, but further verification is needed. Liquid propane seeding produced measurable increases in ice particle concentrations in some experiments, showing it to be an alternative to AgI at only slightly supercooled temperatures.

SUMMARY AND RECOMMENDATIONS

Some of the seeding experiments produced obvious changes in microphysical characteristics and snowfall during periods with very limited natural snowfall. Others produced none, as expected, because of intense natural snowfalls, relatively warm cloud temperatures, drier conditions, or poor targeting of the materials. Natural variability masked some of the results or created misleading control intervals. Though only a few of the experiments were relatively free of such complications, this operational style design with a variety of cloud environments was intentional. It provided a range of conditions likely to be encountered in operational seeding programs. Furthermore, the stress on physical, rather than statistical (see Heimbach and Super, 1996) verification of the experiments provides a basis for seeing what happened with each experiment, even if the natural variability was a complicating factor.

One of the case study experiments (December 15) used an AgI release while cloud temperatures were relatively cold, near -7.8 at the HAS and -10.4 °C at the TAR. The resulting seeded IPC and snowfall was estimated at 140 L⁻¹ and 1.0 mm h⁻¹ respectively, 4.2 km east-northeast of the HAS at the TAR. This experiment provides convincing evidence that AgI seeding can produce significant snowfall under certain conditions.

A second case study experiment (March 5) released liquid propane at HAS cloud and TAR temperatures of -2.1 °C and -4.1 °C, respectively. Propane seeding was estimated to have enhanced IPC by about

30 L⁻¹ and snowfall by 0.25 mm h⁻¹. Higher propane release rates may be appropriate for these slightly supercooled temperatures.

A third case study experiment with AgI seeding, conducted just after the March 5 propane seeding, did not enhance IPC during temperatures near -1.5 °C at the HAS and -3.6 °C at the TAR. It was too warm for the contact-freezing mechanism to operate efficiently, and apparently the forced condensation-freezing mechanism was also ineffective in spite of AgI release within supercooled liquid cloud.

The second experiment of March 11th had a HAS propane release into a cloud temperature of 0.9 °C with TAR temperature of -3.0 °C. This experiment suggests the seeding resulted in about 15 L⁻¹ IPC enhancement at the TAR with perhaps 0.1 mm h⁻¹ snowfall.

These March 5th and March 11th results both argue for improved field documentation of propane effectiveness, especially at temperatures warmer than -5 °C where AgI is believed ineffective. Higher propane release rates seem appropriate for the slightly supercooled temperatures (-1 to -2 °C) experienced at the release site during these two experiments. It may be that the propane rate used, 6000 g h⁻¹, is appropriate for colder cloud temperatures. Unfortunately, no successful propane experiments were conducted when HAS temperatures were in the -2 to -5 °C range.

There is no doubt that propane seeding can increase snowfall at temperatures warmer than -5 °C when excess SLW is available. The questions yet to be answered are what release rate is required to produce significant snowfall and is such a release rate economical? The potential importance of being able to seed slightly supercooled cloud, found in abundance especially in California but throughout the intermountain West as well, is too great to ignore these questions.

Two experiments conducted on January 5th suggested that the forced condensation-freezing mechanism may have increased both IPC and snowfall when HAS temperatures were between -3.0 to -3.7 °C and the TAR was near -5.5 °C. If verified, such warm temperature AgI nucleation would have important ramifications. But additional evidence is needed to ensure that these preliminary suggestions are not simply the result of natural variability. There is little other evidence from this series of 24 experiments on 9 different days that high altitude AgI seeding was effective in IPC enhancement when Plateau top temperatures were warmer than -6 °C.

These experiments have provided valuable information to partially address seeding effectiveness. Data from the subsequent season are now being analyzed. Additional seeding experiments should be conducted on the Plateau between the HAS and the TAR. These experiments are simple and economical, and targeting of the TAR site is routine with southwesterly flow at the HAS. Future experiments of this type should concentrate on periods with no more than very light natural snowfall. Detecting microphysical changes caused by seeding during higher natural snowfall rates is difficult because of the variability of such snowfall.

1998 articles and papers:

8.27. Holroyd, E. W., and A. B. Super, 1998: *Experiments with pulsed seeding by AgI and liquid propane in slightly supercooled winter orographic clouds over Utah's Wasatch Plateau*. *J. Weather Modification*, 30, 51-76.

ABSTRACT

A series of orographic cloud seeding experiments were conducted on Utah's Wasatch Plateau during the 1994-95 and 1995-96 winters. Their purpose was to permit physical assessment of the effect of both silver iodide and liquid propane seeding, particularly at only slightly supercooled temperatures. Seeding materials were released in 1-hour and half-hour pulses from a location well up the plateau's windward slope. The terrain often channeled the seeding plumes to an observation site, or target, located at a canyon head on the Plateau top's windward edge. Snow particles were detected at the target with a vane-mounted 2D-C optical array probe whose strobing speed was governed by a heated anemometer. AgI nuclei were detected there by an NCAR ice nucleus counter to confirm the presence and successful targeting of seeding materials.

The experiments were carried out in conditions both favorable and unfavorable for expected effectiveness of the seeding agents. There was no evidence for the effectiveness of AgI plumes injected into clouds at a release site temperature warmer than about -3 °C and target temperature of about -5 °C. Increases in ice particle concentrations and precipitation rates were observable for AgI seeding with target air temperatures colder than -6 °C.

Liquid propane was released into air at temperatures of -0.4 to -3.4 °C, resulting in about 10 ice particles L⁻¹ at the target with only one release nozzle and about 20 L⁻¹ for two nozzles. The difference in ice particle concentrations formed by adding the second nozzle was statistically detectable at a 6 percent level or better, depending on the measurement type. While a temperature dependence of the liquid propane was not observable over such a small temperature range, the experiments have shown that liquid propane is an effective seeding agent for slightly supercooled clouds at temperatures where AgI is ineffective.

Seeding plume detection appeared to be limited during periods of abundant natural snowfall. The larger natural crystals appeared to compete for the available supercooled liquid water and may have removed many of the seeded embryos by aggregation.

SUMMARY AND CONCLUSIONS

The previous results on the first winter of experiments (Super and Holroyd, 1997) stressed case studies, particularly for those examples with an obvious seeding effect. This paper examines the entire set more from an operational point of view, searching for consistency of increases in concentrations and precipitation rates over all experiments. A natural data set was created to provide an indication of natural variability.

The seeded data set was partitioned into a set of "reject" cases which should appear natural, the AgI cases which should have limited effects at warm temperatures, and the propane cases. The "reject" cases indeed appeared similar to the natural data set. Both the AgI and propane cases showed increases in ice particle concentrations and precipitation rates as measured by the 2D-C for particles up to 0.8 mm sizes. All three partitions showed the same relationships (not presented) and scatter as in Figure 3 between ice particle

concentration and precipitation rate for the natural data set. That indicates that the mass and terminal velocity relationships for seeded crystals were about the same as for natural particles.

The strongest increases were for the propane cases, which had HAS release temperatures ranging only between -0.4 and -3.4 °C. The use of one nozzle produced concentration increases for small particles of about ten L⁻¹ and two nozzles about twenty L⁻¹. Precipitation rate increases of 0.17 mm h⁻¹ for 2 nozzles are admittedly small, but they are a 37% increase over that in the natural data set for the same sizes. Additional growth times for a traverse greater than the 4.2 km should further boost the precipitation rate until the crystals hit the ground somewhere downwind.

No increases were found in the gage measurements for the AgI and propane cases, though the nozzle number analysis showed a strong difference when the second nozzle was added.

The seeded volume of cloud is not known and therefore the total production rate of ice particles cannot be accurately compared to the rate of release of the seeding agents. However, an estimate can be made to examine the order of magnitude. Holroyd et al. (1988) found a plume dispersion angle of about 15 degrees at distances close to the surface release site of AgI generators on the Grand Mesa of Colorado. Using a half-angle from the center line of 7.5 degrees in both the horizontal and vertical directions, the plume cross section at the TAR, 4.2 km downwind from the HAS, can be approximated by a half circle of radius 550 m. The average transit time for the propane experiments was 17.0 min, yielding an average wind speed between the HAS and TAR of 4.1 m s⁻¹. Two nozzles released liquid propane at about 6 to 8 gal h⁻¹ or about 3.7 g s⁻¹, producing about 21 ice particles L⁻¹. Combining the flux of particles through the plume cross section at the TAR and the release rate yields a production rate for liquid propane of about 1.1 x 10¹⁰ particles g⁻¹ between -0.4 and -3.4 °C. Super and Holroyd (1997) quoted other investigators of liquid propane production rates of 10¹⁰ to 3 x 10¹¹, 10⁸ to 10¹¹, and 10¹² particles g⁻¹ at similar temperatures. Finding 10¹⁰ particles g⁻¹ remaining 4.2 km downwind after losses to coagulation and evaporation and to the trees and ground, appears to be of comparable magnitude to those previous estimates.

Operational use of liquid propane, costing \$0.80 gal⁻¹, using two nozzles at 7 gal h⁻¹ indicates a materials cost of \$5.60 h⁻¹ for a seeding unit that produces a plume about a kilometer wide at 4.2 km downwind with an increase of about twenty particles L⁻¹ at only slightly supercooled conditions. The precipitation rate increase according to the 2D-C was 0.17 mm hr⁻¹. According to Table 1, the gage equivalent rate (dividing by 0.56 to convert from 2D-C rates to gage rates) is 0.30 mm hr⁻¹ for the small particles. Additional growth time could result in larger amounts of precipitation.

For comparison, the materials cost for operating a NAWC AgI generator is 8 g h⁻¹ is about \$20 h⁻¹. The production from such a generator is highly dependent on the nucleation temperature.

These experiments show that AgI appears to have no effect when released at similar temperatures and comparable or greater effect at TAR temperatures colder than about -6 °C, though the data are noisy. Therefore the use of liquid propane as a seeding agent at only slightly supercooled temperatures is an effective and inexpensive means to boost ice particle concentrations downwind in orographic clouds.

A future experiment should try to document the fallout pattern with downwind distance of precipitation generated by the use of liquid propane. That could be accomplished in a straight canyon with road from the generator to the crest and beyond. The best experiments will be with only trace natural snowfall, permitting the use of numerous snowboards scattered downwind and crosswind to supplement recording precipitation gages and a mobile 2D-C probe.

These Wasatch Plateau experiments had a relatively simple design involving pulsed seeding from an elevated site on the upwind slopes of a major plateau. The local terrain channeled the plume towards the target 4.2 km away at the windward edge of the crest with good probability of actually hitting that instrumented target. Admittedly, observations taken over the middle or downwind portion of the Wasatch Plateau top likely would have demonstrated increased growth of seeded crystals and associated increases in seeded snowfall. However, such a design, while providing a better simulation of operational seeding from high altitude sites, would greatly reduce the odds of proper targeting. The pulsed seeding style, with AgI tags for the liquid propane cases, allowed numerous experiments during most storm periods. Even so, natural variability of snowfall made it challenging to detect the results of seeding. Periods with none to trace natural snow did show obvious seeding effects. Periods with an abundance of snow or strong showers tended to mask the seeding signal. The large natural crystals 1) dominated the precipitation gage measurements, 2) presumably swept out many of the small seeded crystals through aggregation, hereby lessening their detectability by the 2D-C, and 3) consumed orographic supercooled liquid water (SLW), thereby starving the growing seeded embryos.

The experiments described by Holroyd et al. (1988) showed that AgI released from similar sites on the Grand Mesa were easily detectable at aircraft levels from an abundance of small, growing ice particles. Those experiments had a more complex design (Super, et al., 1988) and were more expensive to carry out in terms of equipment and manpower. Super and Boe (1988) describe some of those experiments during a period of little natural snowfall. Seeding effects were readily observable at aircraft levels, but observations at the surface had variable success in demonstrating the presence of the seeding plume. They suggested that in the "failed" experiments the embryo ice crystals did not have sufficient residence time in the presence of SLW to grow to sizes that would fall to the surface. The Bridger Range experiments described by Super and Heimbach (1988) used aircraft to detect ground-released AgI seeding effects. They were present when SLW was available and absent when it was minimal. It therefore appears that detection of seeding effects is strongly influenced by the amount of time that seeded crystals spend in the presence of SLW. The competition for that SLW by larger natural snow particles and the sweeping action (aggregation) whereby natural crystals remove seeded embryos from the air mean that there may be little or no seeding affects to detect at the surface if there is an abundance of natural snow.

In conclusion, it remains highly desirable to further physically document the effectiveness of winter orographic cloud seeding under various conditions. However, this goal remains challenging even with sophisticated equipment and abundant manpower. Progress has been made under NOAA's Atmospheric Modification Program. However, it seems that future progress is physically verifying weather modifications effectiveness will depend on other sources of support, at least in the near-term.

8.28. Heimbach, J. A., A. B. Super, and W. D. Hall, 1998: *Modeling AgI targeting effectiveness for five generalized weather classes in Utah*. *J. Weather Modification*, 30, 35-50.

ABSTRACT

Rawinsonde observations from the 1991 and 1994 Utah/NOAA field programs were stratified into five classes based on temperature profiles. The classed soundings were used to initialize the Clark mesoscale model to simulate the AgI transport from three operational generator sites in the valley upwind of the Wasatch Plateau in central Utah. The goal was to generalize ranges of conditions which would allow successful targeting of valley-released AgI. Not unexpectedly, the most unstable sounding class produced the best targeting. This class was the coldest of the five, producing more effective ice nuclei from the available AgI because of the temperature dependence of this ice nucleating agent. In general, the modeled

results were in agreement with selected case studies of field observations. Wind characteristics were also shown to be important for successful targeting.

CONCLUSIONS

The purpose of this paper is to describe the general character of transport and diffusion of valley-released AgI under various stability regimes observed in the Plateau region. Five sounding types were partitioned from the 92 soundings taken during the Utah/NOAA AMP 1991 and 1994 field programs. The five composite soundings covered a reasonable span of reality. The Clark model was initiated by each class and run using stimulated releases of AgI from 3 valley sites.

There are several factors highlighted by the modeling applied in this investigation, most of which were confirmed by field observations.

- There is a frequent tendency for a low-level northward drift of valley-released of AgI in the Sanpete Valley.
- Under some circumstances there can be a westward or northwestward drift of AgI in the Sanpete Valley in spite of organized westerly flow aloft.
- Strong upward motion over the lee slopes is possible under some stability and speed conditions because of gravity wave transport.
- Mechanical forcing is important for transport over a barrier.
- Targeting from valley releases is poor for classes D and E which comprise 18% of the soundings released during the 1991 and 1994 field programs.
- Though properly targeted, the effectiveness of the AgI can be handicapped by warm temperatures over the Plateau. This was particularly true for class D which comprises 5% of the soundings.
- Class A appears to hold the best prospects of effective cloud seed because of the successful targeting and characteristic cold temperatures. Thirteen percent of the soundings were class A.

A clear transport and diffusion categorization was evident in the modeling results, implying that modeling of this type could be useful for operational planning. For example, model runs could be made at locations being considered for seeding as demonstrated by Farley et al. (1997). The application of the model must, however, be tempered with interpretive skills. The sensitivity of the model results to wind direction and speed complicate the formation of generalizations. To estimate specific details of a case through modeling, it is preferable to model individually, initializing with the most detailed parameters available.

8.29. Wetzol, M. A., R. D. Borys, and A. W. Huggins, 1996: *Combined Satellite Remote Sensing and Ground-Based Measurements for Evaluation of Cloud Seeding Opportunities and Effects. Workshop on Theoretical and Practical Aspects of Regional Precipitation Enhancement Programme for the Middle East and Mediterranean, Bari, Italy. 12 pp.*

INTRODUCTION

The Atmospheric Sciences Center (ASC) of the Desert Research Institute (DRI) has conducted field programs in weather modification and cloud seeding for more than 30 years, in several states of the U.S.A. and in other countries. These studies have included detailed research on the microphysical structure of cloud, the effects of aerosol on cloud droplet and ice crystal chemistry, and the use of remote sensing instrumentation to characterize cloud evolution and identify seedable conditions. This paper describes some of the recent results of these ongoing efforts.

- II. Satellite remote sensing of droplet-aerosol parameters
- III. Impact of aerosol on cloud microphysical processes
- IV. Ground-based remote sensing of liquid water and vapor distribution

(A good discussion of spatial and temporal SLW distributions on the Wasatch Plateau is given in this section.)

(No summary or conclusions section in this paper)

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MISSION

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.